Federal Aviation Administration – <ins>Regulations and Policies</ins>
Aviation Rulemaking Advisory Committee

Transport Airplane and Engine Issue Area
Loads and Dynamics Harmonization Working Group
Task 14 – Engine Windmilling Imbalance Loads

Task Assignment

DEPARTMENT OF TRANSPORTATION

Aviation Rulemaking Advisory Committee; Transport Airplane and
Engine Issues--New Task

AGENCY: Federal Aviation Administration (**FAA**), DOT.

ACTION: Notice of a new task assignment for the Aviation Rulemaking
Advisory Committee (ARAC).

SUMMARY: Notice is given of a new task assigned to and accepted by the
Aviation Rulemaking Advisory Committee (ARAC). This notice informs the
public of the activities of ARAC.

FOR FURTHER INFORMATION CONTACT:
 Stewart R. Miller, Manager, Transport Standards Staff, ANM-110, **FAA**,
Transport Airplane Directorate, Aircraft Certification Service, 1601
Lind Ave. SW., Renton, WA 98055-4056, telephone (206) 227-2190, fax
(206) 226-1320.

SUPPLEMENTARY INFORMATION:

Background

    The **FAA** has established an Aviation Rulemaking Advisory Committee
to provide advice and recommendations to the **FAA** Administrator, through
the Associate Administrator for Regulation and Certification, on the
full range of the **FAA**'s rulemaking activities with respect to aviation-
related issues. This includes obtaining advice and recommendations on
the **FAA**'s commitment to harmonize its Federal Aviation Regulations
(FAR) and practices with its trading partners in Europe and Canada.
    One area ARAC deals with is Transport Airplane and Engine issues.
These issues involve the airworthiness standards for transport category
airplanes in 14 CFR parts 25, 33, and 35 of the FAR and parallel
provisions in 14 CFR parts 121 and 135 of the FAR. The corresponding
European airworthiness standards for transport category airplanes are
contained in Joint Aviation Requirements (JAR)-25, JAR-E and JAR-P,
respectively. The corresponding Canadian Standards are contained in
Chapters 525, 533 and 535 respectively.

The Task

    This notice is to inform the public that the **FAA** has asked ARAC to
provide advice and recommendation on the following harmonization task:

    Engine Windmilling Imbalance Loads. Define criteria for

establishing the maximum level of engine imbalance that should be considered, taking into account fan blade failures and other likely causes of engine imbalance. Develop an acceptable methodology for determining the dynamic airframe loads and accelerations resulting from an imbalanced windmilling engine. Validate the proposed methodology with a demonstrative ground or flight test program (as deemed appropriate by ARAC) that has the objective of establishing confidence in the proposed methodology. The validation process should answer the following questions: (1) What are the parameters to consider in determining the minimum degree of dynamic structural modeling needed to properly represent the imbalanced condition; (2) Is the proposed analytical methodology taken in conjunction with the traditional ground vibration tests, flight flutter tests, and tests performed under Sec. 33.94 of 14 CFR sufficient, or are there additional tests and measurements that need to be made to address this condition?

Within 12 months from the date of the published notice of new task in the Federal Register, complete the above tasks and submit a report to the **FAA** with recommendations detailing the criteria and methodology.

ARAC Acceptance of Task

ARAC has accepted this task and has chosen to assign it to the existing Loads and Dynamics Harmonization Working Group. The working group will serve as staff to ARAC to assist ARAC in the analysis of the assigned task. Working group recommendations must be reviewed and approved by ARAC. If ARAC accepts the working group's recommendations, it forwards them to the **FAA** as ARAC recommendations.

Working Group Activity

The Loads and Dynamics harmonization Working Group is expected to comply with the procedures adopted by ARAC. As part of the

procedures, the working group is expected to:
1. Recommend a work plan for completion of the tasks, including the rational supporting such a plan, for consideration at the meeting of ARAC to consider Transport Airplane and Engine Issues held following publication of this notice.
2. Give a detailed conceptual presentation of the proposed recommendations, prior to proceeding with the work stated in item 3 below.
3. For each task, draft appropriate documents with supporting analyses, and/or any other related guidance material or collateral documents the working group determines to be appropriate.
4. Provide a status report at each meeting of ARAC held to consider Transport Airplane and Engine Issues.

Participation in the Working Goup

The Loads and Dynamics Harmonization Working Group is composed of experts having an interest in the assigned task. A working group member need not be a representative of a member of the full committee.
An individual who has expertise in the subject matter and wishes to

become a member of the working group should write to the person listed under the caption FOR FURTHER INFORMATION CONTACT expressing that desire, describing his or her interest in the tasks, and stating the expertise he or she would bring to the working group. The request will be reviewed by the assistant chair, the assistant executive director, and the working group chair, and the individual will be advised whether or not the request can be accommodated.

The Secretary of Transportation has determined that the formation and use of ARAC are necessary and in the public interest in connection with the performance of duties imposed on the **FAA** by law.

Meetings of ARAC will be open to the public, except as authorized by section 10(d) of the Federal Advisory Committee Act. Meetings of the Loads and Dynamics harmonization Working Group will not be open to the public, except to the extent that individuals with an interest and expertise are selected to participate. No public announcement of working group meetings will be made.

Issued in Washington, DC, on June 26, 1996.
Chris A. Christie,
Executive Director, Aviation Rulemaking Advisory Committee.
[FR Doc. 96-16960 Filed 7-2-96; 8:45 am]
BILLING CODE 4910-13-M

Recommendation Letter

October 24, 1997
B-T000-ARAC-97-012

BOEING

Mr. Guy Gardner
Associate Administrator for
Regulation and Certification
Department of Transportation
Federal Aviation Administration
800 Independence Avenue, S.W.
Washington, DC 20591

Dear Mr. Gardner:

Subject: Submittal of Loads Imbalance Working Group Final Report

The final report from the Engine Imbalance Loads Working Group was reviewed
by the ARAC TAEIG at their meeting of July 29 - 30, 1997. The report was
unanimously approved for submittal by the ARAC TAEIG Members with one
editorial change. On page 11-1 of the report, last sentence, the wording was
revised as follows: "...level of safety, these criteria ~~should also be assumed to apply
equally~~ [may be applicable] to airplanes...".

The ARAC TAEIG Members wished to take this opportunity to commend the
efforts of this Working Group.

Please accept this letter as formal submittal of the above item. Copies of the
submittals have been previously sent to FAA Office of Rulemaking.

The members of ARAC TAEIG appreciate the opportunity to participate in the
FAA rulemaking process.

Sincerely,

Ed A. Kupcis
Chief Engineer,
Certification Requirements,
Boeing Commercial Airplane Group
Tele: (425) 234-4304, FAX: (425) 237-4838

Acknowledgement Letter

U.S. Department
of Transportation

**Federal Aviation
Administration**

800 Independence Ave., S.W.
Washington, D.C. 20591

JAN 2 3 1998

Mr. Craig Bolt
Aviation Rulemaking Advisory Committee
Pratt & Whitney
400 Main Street
East Hartford, CT 06108

Dear Mr. Bolt:

This letter is in response to Mr. Ed Kupcis' letter in which he submitted the Engine
Windmilling Imbalance Loads Final Report. This report establishes acceptable criteria
and methodology for determining the dynamic airplane loads and accelerations resulting
from an imbalanced windmilling engine.

I would like to thank the Engine Imbalance Loads Working Group and the aviation
community for its expenditure of resources to develop this Final Report, and its
commitment to the Aviation Rulemaking Advisory Committee. A draft advisory circular
on this final report is anticipated early 1998.

Sincerely,

Guy S. Gardner
Associate Administrator for
    Regulation and Certification

Recommendation

Engine Windmilling Imbalance Loads

Final Report - July 1, 1997

Aviation Rulemaking Advisory Committee

Engine Imbalance Loads Working Group

DRAFT

1.   Contents

ARAC Engine Imbalance Working Group

Membership

Partha Mukhopadhyay (Chairman)	Boeing
Jeff Bland	Boeing
Chet Lewis	Boeing
Carl Neidermeyer	Boeing
Wayne Tygert	Boeing
Bob Wilkinson	Boeing
Christian Beaufils	Airbus
Jean-Yves Beaufils	Airbus
Michel Lacabanne	Airbus
John Galligher	Douglas
Amos Hoggard	Douglas
Bill Barron	Lockheed
Tony Linsdell	Canadair
Doug McKissack	Gulfstream
Brian Adams	Rolls-Royce
Dave Klassen	GE
Eduord Jadczak	SNECMA
Mike Pollard	Pratt & Whitney
Mike Romanowski	Pratt & Whitney
Al Weaver	Pratt & Whitney
Jim Haynes	FAA
Lanny Pinkstaff	FAA
Jay Turnberg	FAA
Vic Card	JAA

Executive Summary

This report is submitted to complete the task published in the Federal Register (Vol. 61, Number 129) on July 3, 1996 and assigned to the Aviation Rulemaking Advisory Committee (ARAC) entitled "Engine Windmilling Imbalance Loads." This report details the work performed in establishing an acceptable criteria and methodology for determining the dynamic airplane loads and accelerations resulting from an imbalanced windmilling engine. The conclusions and recommendations of this report represent the fully agreed position of the Loads and Dynamics Harmonization Working Group.

This report addresses fan blade failure events as well as other likely causes of significant engine vibratory loads such as loss of centerline support.

Thorough examination of all known events indicates that none resulted in significant airplane damage and all resulted in continued safe flight and landing. However, an examination of the existing criteria did not identify any specific requirements that would continue to guarantee the positive outcome experienced in the known events. Therefore, the working group developed recommended criteria to assure safety of flight in all future airplanes in the event of windmilling under engine imbalance.

The criteria recommended in this report are applicable to high bypass ratio engines with fan diameters greater than 60 inches. In the absence of evidence justifying an alternative approach providing an equivalent level of safety, these criteria should also be assumed to apply equally to airplanes with smaller diameter engines.

Based on statistical analysis of the service history data of large high bypass ratio engines under windmilling imbalance condition, design evaluation criteria have been developed to ensure continued safe flight and landing following a fan blade loss event.

This is accomplished by establishing the maximum level of engine imbalance and associated diversion times to be used for analytical determination of the airplane loads and accelerations.

Recommendations are included addressing the level of detail required for engine and airframe modeling to adequately describe the dynamic characteristics needed to provide valid loads and accelerations. The working group reviewed the traditional ground vibration tests, flight flutter tests, and tests performed under Sec. 33.94 of 14 CFR and concluded that no further demonstrative ground or flight test programs would be needed in order to achieve the objective of establishing confidence in the proposed methodology.

The working group recommends that a harmonized FAR Part 25 Advisory Circular and an ACJ to JAR 25 be developed based on the technical information contained in this report.

2.   Introduction

The gradual evolution of the turbofan engines has led to the introduction of engines with increasing bypass ratio to achieve high fuel efficiency. These engines have the same propulsion principle as the earlier generation high bypass ratio engines. A gas turbine drives a multi-bladed fan that accelerates the oncoming airmass, generating thrust for propelling the aircraft. A small amount of jet thrust is also provided from the engine core. Need for higher efficiency and greater robustness has resulted in fan design consisting of fewer blades of larger mass than previously used.

In the service experience of the existing high bypass ratio engines there had been instances, though very rare, of blade loss and even more rarely, fan shaft support loss. In most cases the fan continues to rotate producing an imbalance load even after the engine combustor has been extinguished. This phenomenon is called imbalance load under engine windmilling. In all cases the airplane safely landed with no other significant damage to the airplane, and without any injury to the passengers or crew.

With the advent of heavier fan blades, the FAA became concerned whether the past design practice that resulted in safe designs will continue to produce safe design for the new engine–airframe combinations. To address this concern the FAA is requiring detailed evaluation of airplanes by means of Issue Papers on new certification programs. In these Issue Papers, the FAA has cited existing sections of the FAR Part 25 as the basis for compliance. The Issue Paper process does not afford sufficient sharing of knowledge with the industry as a whole and the FAA. Therefore, to address the issue the Aviation Rulemaking Advisory Committee (ARAC) has assigned a task to the Loads and Dynamics Harmonization Working Group that consists of experts in this field. The task has been published on July 3, 1996 in the Federal Register, Vol. 61, Number 129, and is reproduced below.

"*The Task—This notice is to inform the public that the FAA has asked ARAC to provide advice and recommendation on the following harmonization task:*"

"*Engine Windmilling Imbalance Loads. Define criteria for establishing the maximum level of engine imbalance that should be considered, taking into account fan blade failures and other likely causes of engine imbalance. Develop an acceptable methodology for determining the dynamic airframe loads and accelerations resulting from an imbalanced windmilling engine. Validate the proposed methodology with a demonstrative ground or flight test program (as deemed appropriate by ARAC) that has the objective of establishing confidence in the proposed methodology. The validation process should answer the following questions; (1) What are the parameters to consider in determining the minimum degree of dynamic structural modeling needed to properly represent the imbalanced condition; (2) Is the proposed analytical methodology taken in conjunction with the traditional ground vibration tests, flight flutter tests, and tests performed under Sec. 33.94 of 14 CFR sufficient, or are there additional tests measurements that need to be made to address this condition.*"

"*Within 12 months from the date of the published notice of new task in the Federal Register, complete the above task and submit a report to the FAA with recommendations detailing the criteria and methodology.*"

In this report a thorough review of the service history of high bypass ratio engines under windmilling imbalance condition is presented. The service history data have been examined by the engine companies, the aircraft manufacturers, and the FAA and JAA specialists. Based on the evaluation of the service history data, recommendations have been made on design evaluation criteria.

Extensive industry experience of ground and flight testing pertaining to dynamic behavior of the airframe–engine combination has been reviewed. Analytical results have been correlated with the test results. Appropriate methodology for determining airframe loads and accelerations are presented. The methodology has been essentially validated by ground and flight tests currently performed to satisfy various sections of the 14 CFR.

3. Service History

The service history of large high bypass ratio turbofan engines from entry into service up to May 1996 is comprised of 426 million engine flight hours. During this period 152 notable events have occurred. A notable event represents either a condition where an imbalance equivalent to one fourth of a fan blade or greater is experienced, or a condition resulting from the failure of a support element of the rotor. (Large is defined as engines with a fan diameter of 60 inches or greater. Engine flight hours are defined as the time period from the start of takeoff roll to touchdown.) While events involving loss of fan blade material equivalent to less than one fourth of a blade have occurred in service, these have not caused significant vibrations. The fan blade loss events are more common than fan rotor support loss events: 146 vs. 6. In this chapter the service history data for both of these imbalance conditions are analyzed.

Fan Blade Loss

Fan blade loss has occurred in service for various reasons, for example, bird strike, foreign object ingestion and high and low cycle fatigue. Service history data indicates a gradual improvement in the robustness of the fan blades as a result of the industry's effort to improve all aspects of fan blade design, manufacture, and maintenance. Though significant improvement has been achieved over time, to be conservative, the entire service history is considered as a single set.

The available service history data consist of blade loss material release fractions and subsequent windmilling time for large modern high by-pass ratio turbofan engines. The database includes events occurring from entry into service through May 1996, a period of approximately three decades. A total of 146 events in the resulting database are used for statistical analysis.

Where additional tests can contribute to further increase confidence, they have been identified.

This report completes the above mentioned task assigned to the Loads and Dynamics Harmonization Working Group.

distributions may be more realistic for predicting the behavior of future events since they are weighted by the bulk of the data. Thus, the effect of potentially anomalous data at the extreme end of the sample is damped which reduces overly conservative estimates of events.

Histograms of design fraction and windmill time are shown in Figures 3.1 and 3.2 together with the actual numbers of events. The histograms are included in modified form in other figures for comparison with the distribution fits.

The data were tested for fit using three different statistical distributions: gamma, Weibull and lognormal. These distributions were chosen because they do not have negative values and they can be shaped to minimize the effect of the lack of data between 0 and 0.1 IDF (0.25 blade fraction) where data was not collected.

The parameters for the gamma, Weibull, and lognormal distributions are obtained by finding the maximum likelihood estimators (MLE) for each of the distributions based on the data sets. Once the parameters are determined, the data are compared graphically to the distribution in two ways.

The first comparison is of the three distributions to a normalized histogram of the data. The area under the normalized histogram is one. This allows comparison against a probability density function (pdf) and is shown in Figure 3.3a. All three of the distributions follow the same trend, but the gamma pdf and the lognormal pdf follow the shape of the histogram more closely. The peak of the lognormal pdf is slightly closer to the peak of the histogram than the gamma pdf.

The primary parameters used in the statistical analysis are imbalance design fraction (IDF) and the windmilling time . Windmilling time is defined as the time in minutes from blade release to landing. An IDF of 1.0 is defined as the mass imbalance that would result from failure of the most critical turbine, compressor, or fan blade under the conditions specified for the blade containment and rotor imbalance tests in section 33.94 of 14 CFR. Blade fraction is defined as the vector sum of the mass moments of the lost rotor material divided by the mass imbalance of one blade removed at the dovetail fillet. Mathematically this value is expressed as:

$$Blade\ Fraction = \frac{\sqrt{\left(\sum_{i=1}^{n} m_i \cdot r_i \cdot \cos\theta_i\right)^2 + \left(\sum_{i=1}^{n} m_i \cdot r_i \cdot \sin\theta_i\right)^2}}{m_b \cdot r_b}$$

Where,

m = a missing rotor mass

r = the radius from the rotor center to the center of gravity of m

θ = an angle measured from a fixed axis (normal to the axis of rotation) to the radial line, r

And subscripts are,

i identifies the ith missing mass of n items

b identifies a removed blade

The statistical analysis is used to derive exceedance curves, and thus to determine exceedance rates over a wide range of IDF and windmilling time values. In order to accomplish this task, the cumulative distribution functions (CDF) for the IDF and windmilling times were generated. At least two methods could be used to generate the CDF's for the two distributions. The first would be to use the ranked raw data, and the second would be to use continuous distributions. There are good reasons for considering both approaches. The raw data is the historical record with all of the events included, even those that may be considered anomalous. The perspective provided may be useful in bounding the issues considered in this document. However, the continuous

top of climb without fuel dump, and any event which occurs up to top of climb with a fuel dump before return, respectively. The Weibull distribution appeared to fit slightly better than the other two distributions but the lognormal distribution is chosen for further analyses since it is most conservative at the high end of the distribution.

Figure 3.5 shows a scatter plot of windmill time versus design fraction. The correlation coefficient (R^2) between blade fraction and windmill time was computed for a linear fit to be 0.05. Based on R^2, IDF and windmill time are statistically independent of one another. Thus, the joint probability function is defined as follows:

$$P(x, w) = (1 - F_X(x))(1 - F_W(w))$$

where:

P	= probability of an event with $X \geq x$ and $W \geq w$.
x	= imbalance design fraction
w	= windmill time (minutes)
F_x	= CDF for imbalance design fraction
F_w	= CDF for windmill time (minutes)

The joint probability function is used to calculate the probability of having an event with an IDF of x or greater, and a windmill time of w or greater.

The exceedance rate curves are generated using the previously defined joint probability function with the number of reported fan blade separation incidents which occurred in flight and the corresponding total number of hours accumulated by all large high bypass ratio engines. The formula used to calculate the exceedance rate is:

$$Exceedance\ Rate = \frac{N_I \cdot P(x, w)}{C_T}$$

where:

C_T = total number of engine flight hours in database
N_I = number of reported incidents in database above V_1

Note that the exceedance rates are based on the number of fan blade loss events that occurred during the flight phase; i.e., at speeds greater than decision speed (V_1). If one were to include all blade loss events from start of takeoff roll to airplane stop after landing, the exceedance rate would be approximately thirty percent greater than that computed for the 124 in flight events. However, the resulting probabilities would then require scaling by the probability that the blade release event occurred in flight (about

The second graphical method compares the MLE distributions against the ranked data for the CDF and $1 - CDF$. This is accomplished by ordering the data and assigning an order number, i. The CDF is estimated as follows:

$$CDF(i) = \frac{i - 0.3}{N + 0.4}$$

where:
N = total data points that occurred in flight
i = order number

The comparisons of the MLE distributions against the ranked data for design fraction are shown in Figures 3.3b and 3.3c.

A correlation coefficient (R^2) estimate of the fitted distributions has been determined. These are seen in Figure 3.3c, along with plots of the CDF. The lognormal distribution has a greater value of R^2 than the other two distributions.

The parameter estimates are listed in Figure 3.3b and shows $1 - CDF$, which is the probability of that event or greater occurring. The tails of the distributions in Figure 3.3b shows that the lognormal distribution will give the highest probability for a given event or larger, making the lognormal distribution the most conservative at the high end of the distribution.

Since the lognormal distribution gives the best representation of the data and is the most conservative for extreme values, it is used to represent the IDF distribution in the rest of the analyses.

The statistics for windmilling event duration after blade loss are also fitted with the three types of distributions. Similar comparisons that are shown in Figure 3.3 for imbalance design fraction are shown in Figure 3.4 for the windmilling duration. The reporting of windmill times is typically split into 10 minute increments, causing difficulty in fitting a continuous distribution. In addition there are three notable clusters at twenty, thirty, and fifty minutes. These times are typical of events which occur early in climb and

Engine Rundown and Shutdown Experience

Service experience indicates that rundowns occur at all levels of blade fraction within the database. Engines which have experienced a full blade loss or more have always rundown to idle or below within a few seconds after blade release. All were shut down by the flight crew within a few seconds after rundown.

Rundown experience is less clear for blade fractions less than one. The consensus of the engine manufacturers is that 20 seconds run-on for self shutdown or crew intervention is a reasonable time for blade fractions greater than 0.50 but less than 1.0. Some events between 0.25 and less than 0.5 blade fraction may run on indefinitely unless the crew takes action to shut down the engine. Although these events cause higher frequency vibration than windmilling events and are not a threat to the airplane structure they have caused crew confusion as to which engine should be shut down. Engine secondary damage resulting from the run on at power has in some cases caused engine conditions which could be hazardous to the airplane (for example through an engine fire). Consideration should be given to ensure that on future airplane designs the crew members are able to make the decision to shut down the appropriate engine in a timely manner.

Fan Rotor Support Loss

Service history database contains six events where fan rotor support loss has resulted in moderate to heavy vibration as characterized by crew comments. These events are shown in Table 3.1. In all cases the crew were able to fly the airplane to complete a safe flight and landing. There were no reports of airplane damage beyond loss of some small access panels and minor structural element cracks (which were not substantiated as being caused by the event) for any of the support loss events. There are six fan rotor support loss events, giving an estimated cumulative probability of 1.41×10^{-8} per engine flight hour. However, five of the events have occurred since 1995 leaving a twenty year gap between the first event. When this data is viewed from a three year rolling rate perspective the rates are about three times greater. A cumulative rate comparison of FBO and loss of support events is shown in Figure 3.7

0.76), bringing the result back to the one in the above equation. The engine hour exceedance rates for various design fractions and windmill times are shown in Figure 3.6. The joint probability function used in this calculation was generated using the lognormal distributions for IDF and windmilling time. The reader may substitute the actual data CDF's to obtain an actual data estimate of the exceedance curves if desired.

Exceedance rates in airplane hours may be obtained from Figure 3.6 by multiplying the ordinate by the number of engines used on the airplane.

A conservative estimate of the impact of including the loss of centerline support events in the analysis showed that the exceedance values at 1.0 IDF and windmilling times greater than zero, 60 and 180 minutes increased to 3.5×10^{-8}, 6.3×10^{-9} and 1×10^{-10} per engine flight hour, respectively. These changes to the exceedance estimates would not alter the conclusions drawn in this report.

Table 3.1 Fan Rotor Support Loss

Date	1/5/96	8/17/74	12/5/95	3/6/96	8/14/95	7/21/95
Landed Safely	Yes	Yes	Yes	Yes	Yes	Yes
Vibration [1]	Moderate/High	High	High	High	High	High
Rubbing	Yes	Yes	Yes	Yes	Yes	Yes
Permanent Shaft Deflection	No	Yes	No	---	No	No
Bearings on Shaft [2]	1-1-0-0	0-1	0-1	0-1	1-0	0-1-1
CAAM Hazard Level [3]	0	1d	1d	0	0	0

1 Based on crew comment
2 The designations in this row represent the bearing configuration on the low rotor
   of the engine type represented in the event.
   A "0" indicates a loss of centerline at that station (a bearing failure or a decoupled
     bearing support or both).
   A "1" indicates a sound bearing and support.
3 CAAM (Continued Airworthiness Assessment Methodology) hazard level 1d signifies
minor damage to the airplane. In these cases it was the loss of access panels, or wing tip
antennae, or minor strut secondary structure cracking.

In loss of support events, the induced vibration results from the displacement of the center of the mass of the fan or turbine from the geometric center of the rotating system. The rotor displacement is controlled by a combination of gaps in the shaft support system and shaft deflection due to the elastic and (sometimes) plastic deformation of the rotor shaft.

As seen in Table 3.1, loss of a bearing support can result in crew reports of high vibration. However, even in these cases the airplanes were landed safely. Investigation of these airplanes showed that the primary structure sustained no damage. From this service experience, it is concluded that current airplanes should have adequate strength to meet this condition. However, this may not always be the case, especially if new airplane designs are significantly different from conventional configurations in vertical and longitudinal mass distributions of fuel, payload, engine location, etc. and operational roles. Without a specific "loss of centerline support" condition, the current engine failure requirements do not guarantee that the necessary static and fatigue strength will always be present. Therefore, consideration has been given to the introduction of a specific "loss of centerline support" condition in addition to the fan blade imbalance condition. Recommended criteria for both of these conditions are given in Chapter 4.

Figure 3.2

Distribution of Imbalance Design Fraction Events
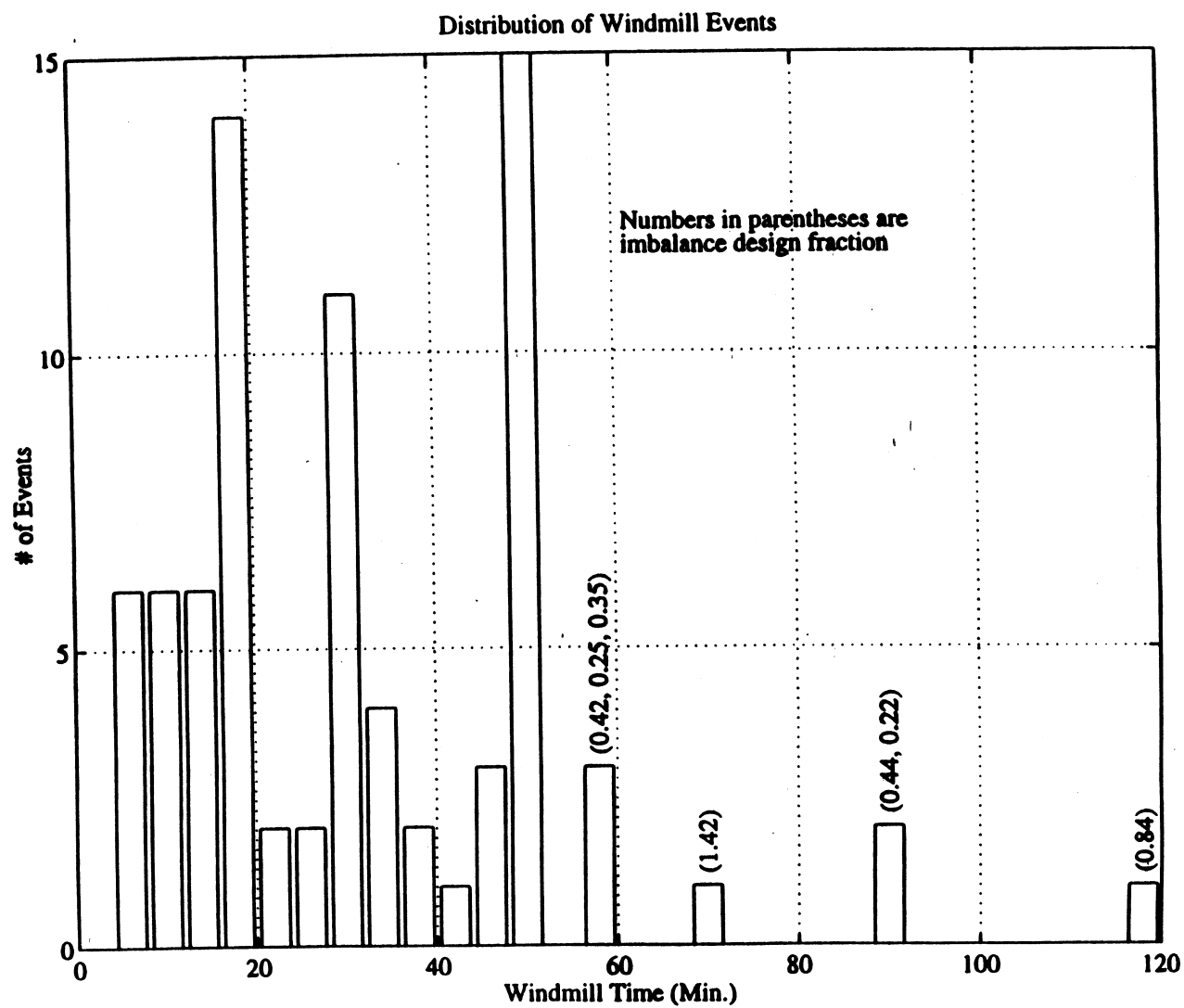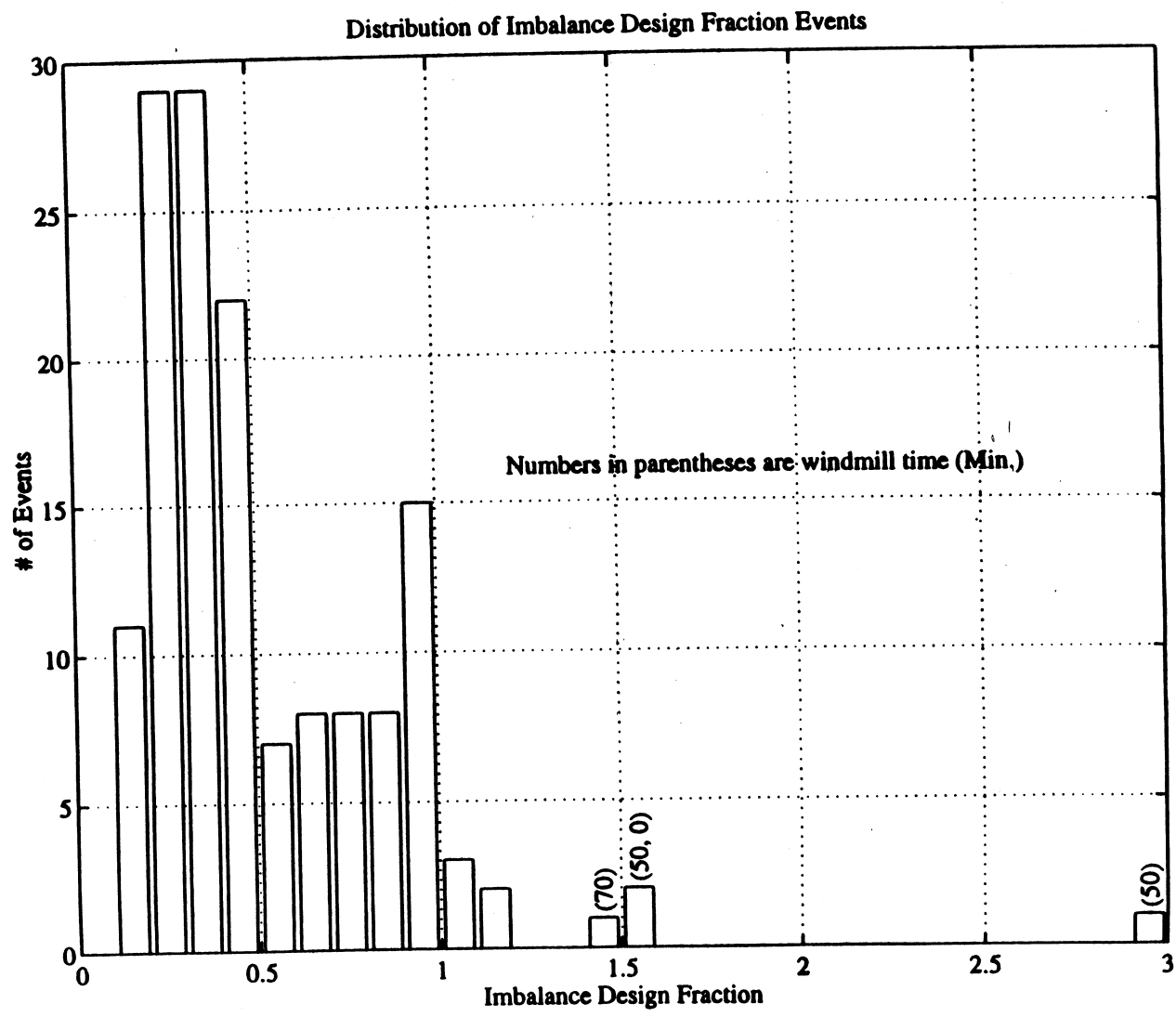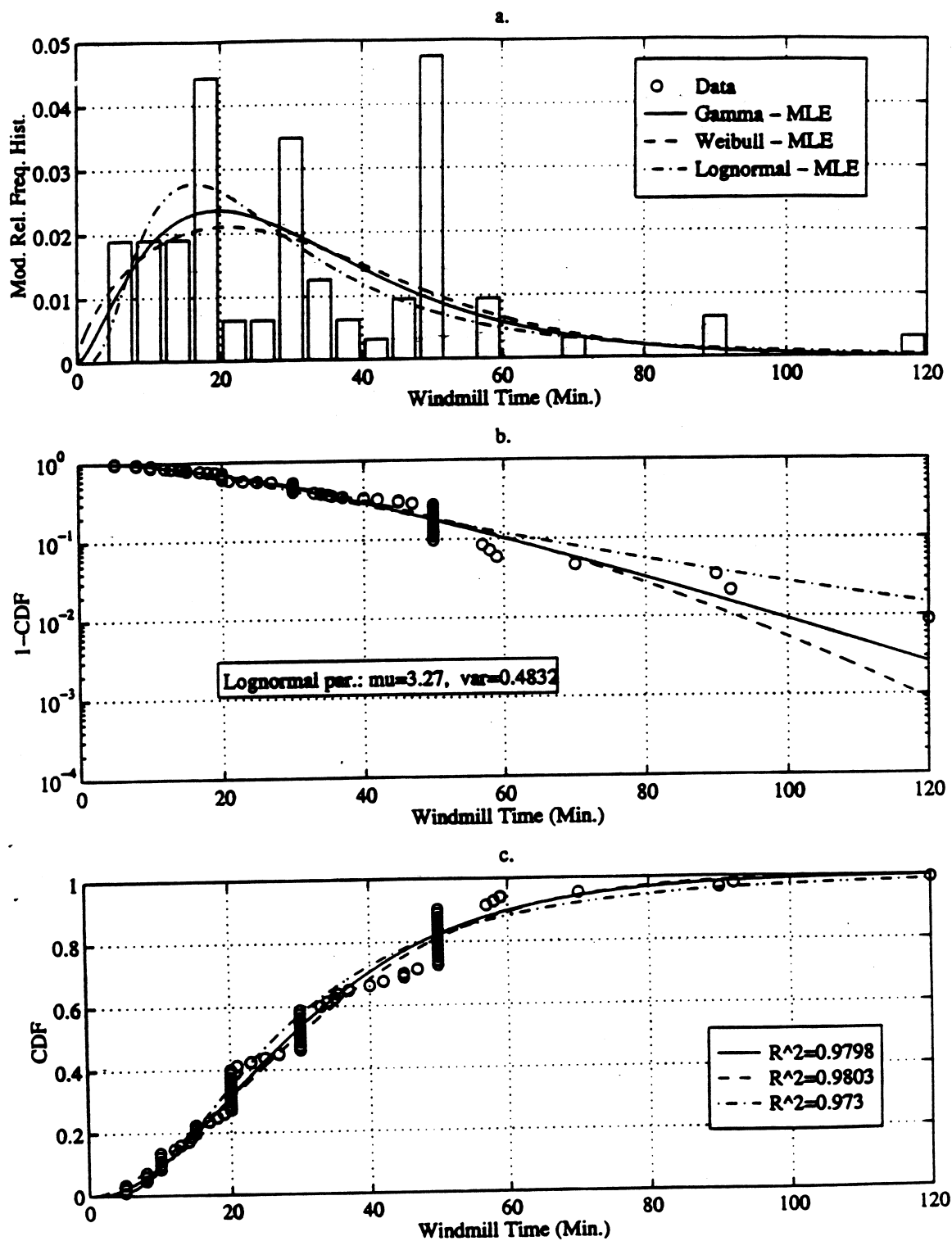
Figure 3.1

2–May–97

foodb1 fjad_dist_prth

Maximum Likelihood Estimation for 3 Distributions – 79 Data Points – fbodb1

a.

b.

Lognormal par.: mu=3.27, var=0.4832

c.

R^2=0.9798
R^2=0.9803
R^2=0.973

2–May–97   Figure 3.4   fbodb1 find_dist

3-13

Maximum Likelihood Estimation for 3 Distributions – 146 Data Points – fbodb1

a.

b.

Lognormal par.: mu=–0.7957, var=0.3372

c.

Figure 3.6

Scatter Plot of Imbalance Design Fraction and Windmill Time
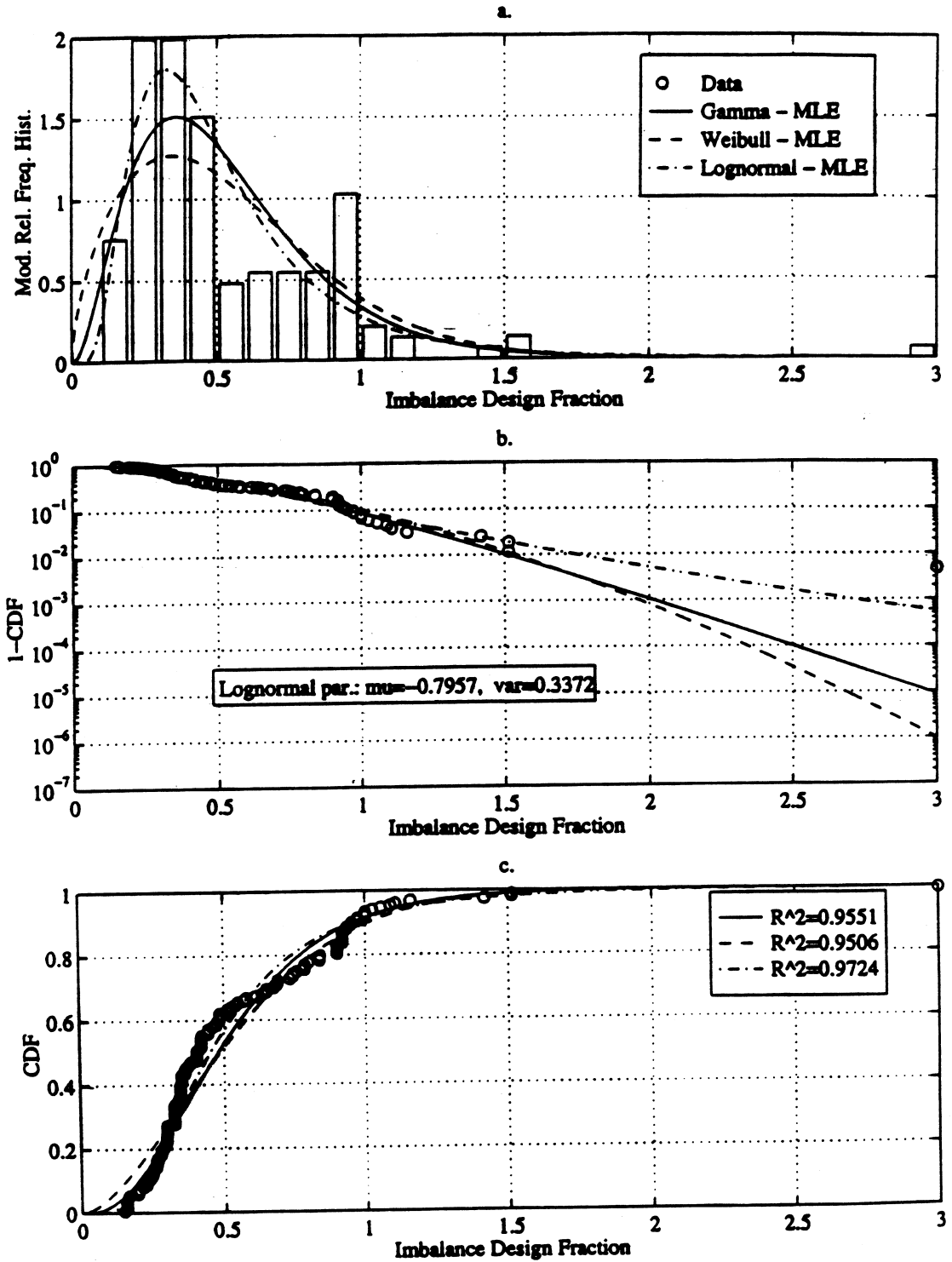
Figure 3.5

2-May-97
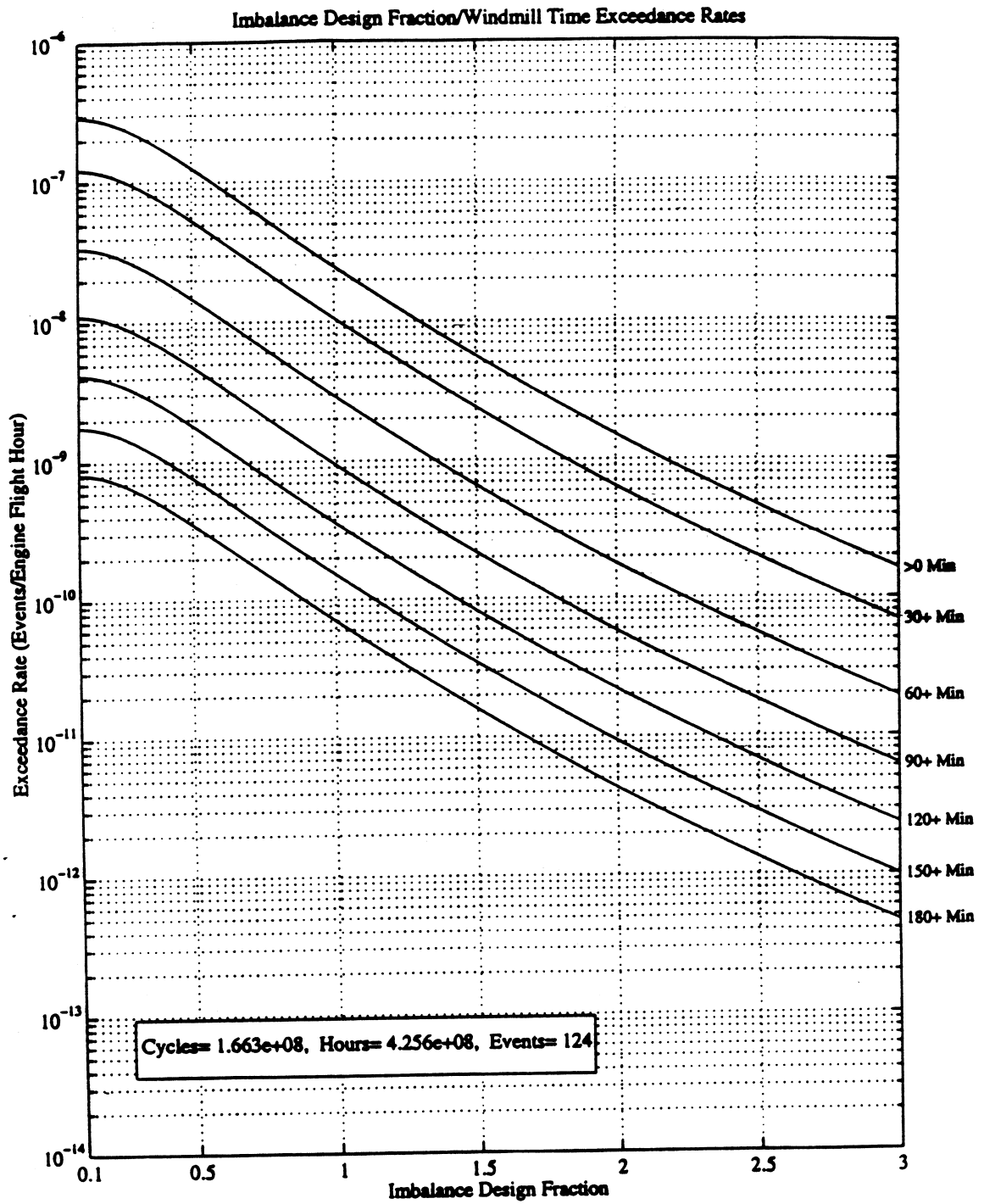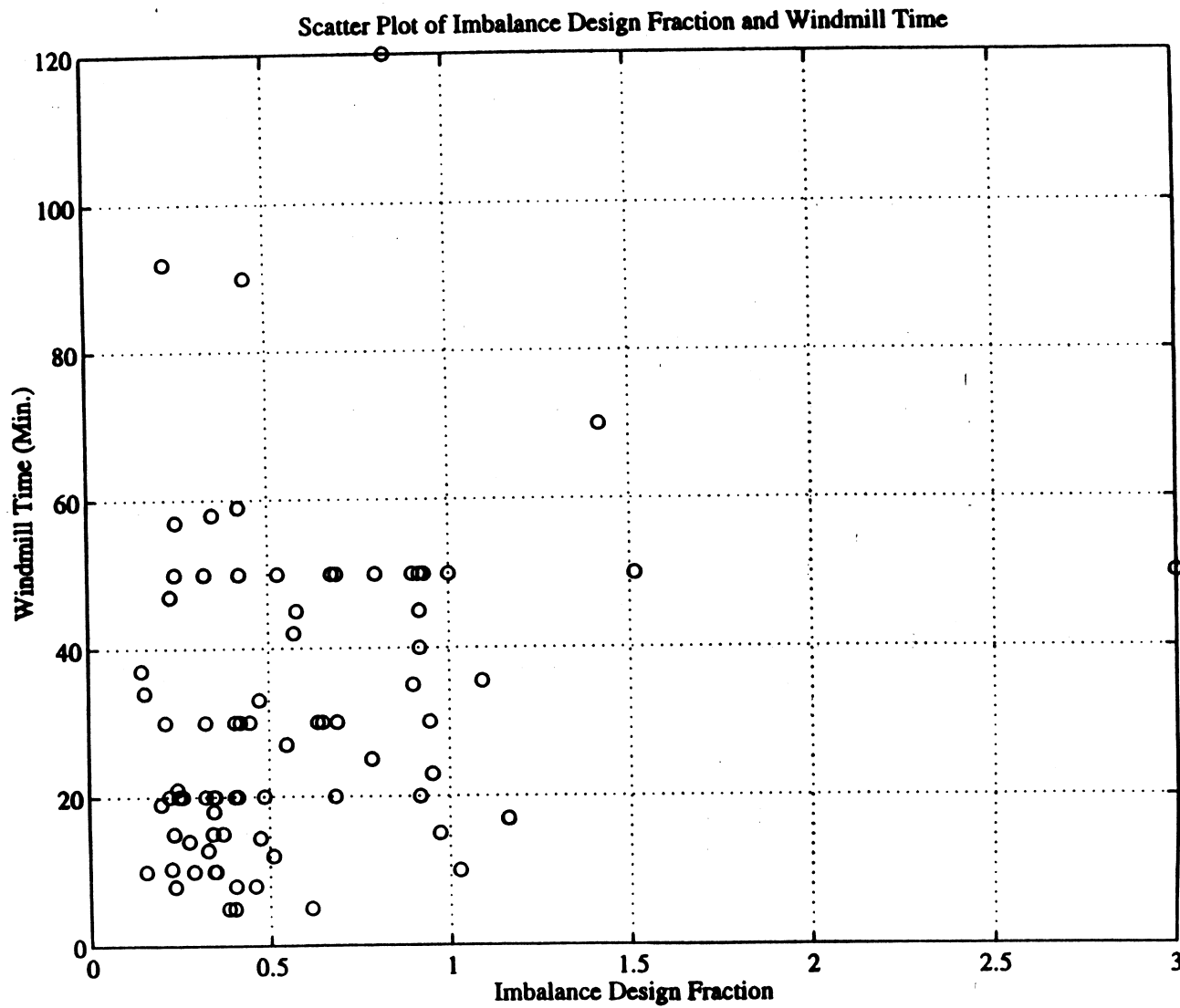
4.   Recommended Criteria

In this chapter the recommended criteria for engine windmilling imbalance load are presented. These criteria apply to airplanes with high bypass ratio engines with fan diameters greater than 60 inches. In the absence of evidence justifying an alternative approach providing an equivalent level of safety this criteria should also be assumed to apply equally to airplanes with smaller diameter engines. The requirements are intended to ensure continued safe flight and landing following a blade loss event. This is accomplished by defining windmilling conditions for evaluation of structure, systems including operating engine(s), and flight crew performance under the vibratory loads resulting from engine windmilling with imbalance. The level of imbalance recommended is an imbalance design fraction (IDF) of 1.0. An IDF of 1.0 is equal to the level of mass imbalance that would result from engine tests required under section 33.94 of 14 CFR. The windmilling duration required for evaluation should account for the maximum diversion profile appropriate to the airplane model, but not exceeding 180 minutes for any given engine and airframe configuration. The fleet service data presented in Chapter 3 show that the combined probability of having an IDF of 1.0 along with a 180 minutes diversion is less than 10^{-9} per airplane flight hour. In light of this, it is recommended that this condition should be evaluated using nominal and realistic flight conditions and parameters.

A recommended methodology is presented for the structural evaluation that consists of static strength, fatigue, and damage tolerance analyses. Additional evaluations for other factors such as systems and flight crew performance should also be considered. These additional evaluations, while out of the scope of this task, should use criteria recommended here for definition of the windmilling conditions.

The criteria presented pertain to sustained imbalance due to fan blade loss events. The criteria do not specifically address situations where the engine does not shut down

4-1

Figure 3.7 Fan Rotor Blade and Support Loss Rate Trends
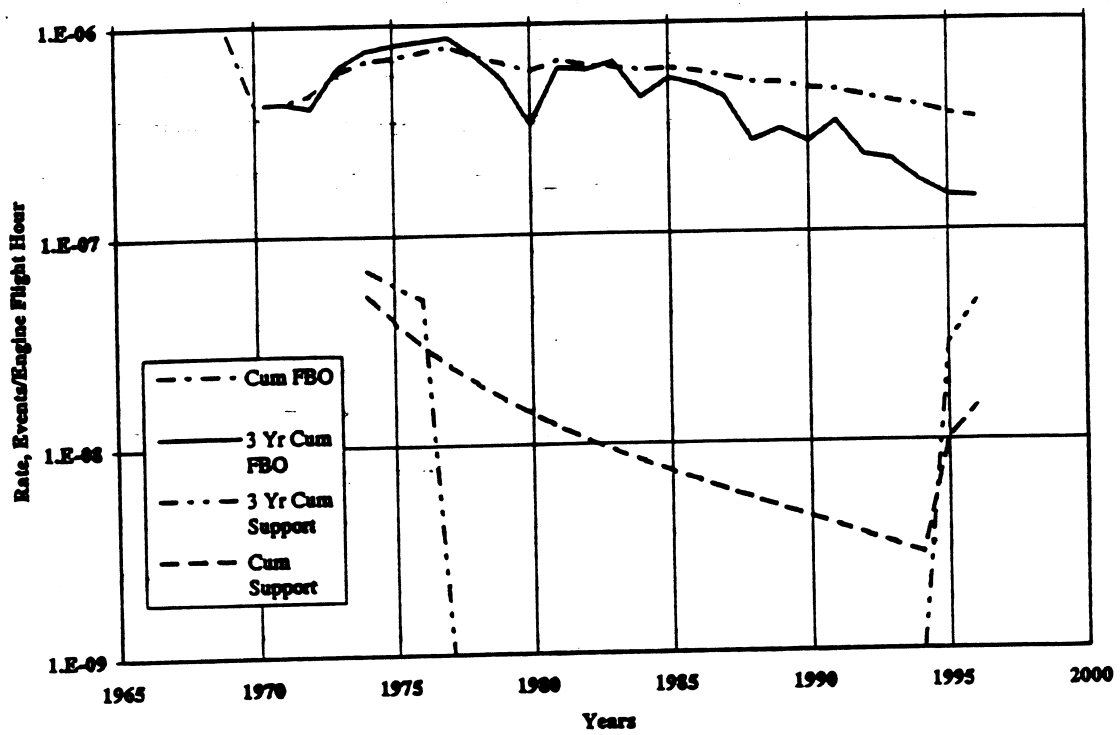
2. Windmilling Vibration Loads

Loads on the airplane components should be determined by dynamic analysis. The analysis should take into account unsteady aerodynamic characteristics and all significant structural degrees of freedom including rigid body modes. The vibration loads should be determined for the significant phases of the diversion profiles described in 1(a) and 1(b). The significant phases are:

(a) an initial phase during which the pilot establishes a cruise condition,

(b) the cruise condition,

(c) the descent phase, and

(d) the approach to landing phase

The flight phases may be further subdivided to account for variation in aerodynamic and other parameters.

The calculated loads parameters should include the accelerations needed to define the vibration environment for the systems and flight deck evaluations.

3. Static Strength Analysis

(a) The primary airframe structure should be shown capable of sustaining the flight and windmilling vibration loads combinations defined in (i), (ii), and (iii) below.

(i) The peak vibration loads for the flight phases described in (2)(a) and 2(c) combined with appropriate 1g flight loads. These loads are to be considered limit loads, and a factor of safety of 1.375 shall be applied.

(ii) The peak vibration loads for the approach to landing phase described in (2)(d) combined with appropriate 1g flight loads and incremental loads corresponding to a positive limit symmetric

immediately following the fan blade loss event. Recommendations are also proposed for the loss of rotor support condition discussed earlier in Chapter 3.

1.   Windmilling Condition Definition

The airplane is assumed to be in level flight with typical payload and realistic fuel loading. The speeds, altitudes, and flap configurations considered may be established in accordance with airplane flight manual (AFM) procedures. Unless it can be shown otherwise, the engine fan shaft is assumed to be windmilling with a rotating imbalance resulting from the loss of fan blade material. An IDF of 1.0 shall correspond to the mass imbalance that would result from failure of the most critical turbine, compressor, or fan blade under the conditions specified for the blade containment and rotor imbalance tests in section 33.94 of 14 CFR. Significant changes in structural stiffness and geometry within the engine that would result from the specified blade failure conditions should be accounted for.

The following conditions should be evaluated using assumptions consistent with the probability of occurrence (Reference Chapter 3) :

(a)   1.0 IDF in conjunction with the maximum diversion time of the airplane, but limited to a maximum of 180 minutes.

(b)   1.0 IDF in conjunction with a 60 minute diversion.

For multiple load path "fail-safe" structure, where it can be shown by observation, analysis, and/or test that a load path failure, or partial failure in crack arrest structure, will be detected by general visual inspection prior to the failure of the remaining structure, either a fatigue analysis or damage tolerance analysis may be performed to demonstrate structural capability. All other structure should be shown to have capability using only the damage tolerance approach.

(a)   Fatigue Analysis

If a fatigue analysis is used for substantiation of a multiple load path "fail-safe" structure then the total fatigue damage accrued during the well phase and the windmilling phase should be considered. The analysis should be conducted considering the following:

(i)   For the well phase, the fatigue damage should be calculated using an approved load spectrum (such as used in satisfying the requirements of FAR(JAR) 25.571)) for the duration specified in Table 4.1. Average material properties may be used.

(ii)   For the windmilling phase, fatigue damage should be calculated for the diversion profiles using a mission that envelopes the AFM recommended operation accounting for transient exposure to peak vibrations as well as the more sustained exposures to vibrations (ref. 2(a) through 2(d)). Average material properties may be used.

(iii)   For each component the accumulated fatigue damage due to 4(a)(i) and 4(a)(ii) multiplied by the appropriate factor (if any) specified in Table 4.1 should be shown to be less than or equal to the fatigue damage to failure.

balanced maneuvering load factor of 0.15g. These loads are to be considered limit loads, and a factor of safety of 1.375 shall be applied.

(iii) The vibration loads for the cruise phase described in (2)(b) combined with the appropriate 1g flight loads and 70% of the flight maneuver loads and, separately, 40% of the limit gust velocity (vertical or lateral) as specified at V_c up to the maximum likely operational speed following the event. These loads are to be considered ultimate loads.

(b) In selecting material strength properties for the static strength analysis, the requirements of section 25.613 apply.

Note: The factor of safety (1.375) was chosen using the criterion that has been applied as a special condition for the interaction of systems and structure. That criterion allows the factor of safety to vary from 1.5 at a rate of occurrence of 10^{-5} per hour to 1.25 at 10^{-9} per hour. The database has been conservatively interpreted as justifying a rate of occurrence of 10^{-7} per hour for the 1.0 IDF event resulting in the 1.375 factor of safety. This conservatism is justified for the sustained imbalance condition because of the many applications of the load as the resonant peak is traversed.

4.   Assessment of Structural Durability

Requirements for fatigue and damage tolerance evaluations are summarized in Table 4-1. Both Conditions 1(a) and 1(b) should be evaluated. The specific conditions listed represent two different targets for structural durability based on the overall probability of the event occurring. Condition 1(a) is established at a 50% probability and condition 1(b) is established at a 95% probability.

Table 4.1 - Fatigue and Damage Tolerance Criteria
for
Windmilling Event

Cond	Desc	Fatigue[1,3] (average material properties)			Damage Tolerance[1,2] (average material properties)		
		Well Phase	Wind-milling Phase[3]	Criteria	Well Phase	Wind-milling Phase[3,4]	Criteria
1a	1-IDF 180 Min. Max[6]	Damage[7] due to 1 DSG	Damage[7] due to 180 minute max[6] diversion with an IDF =1.0	The total damage[7] due to the well phase and the windmill phase[3] ≤1.0	MQF[5] grown for 1/2 DSG	Additional crack growth for a 180 minute max[6] diversion with an IDF = 1.0	Positive M.S. wrt residual strength due to the limit loads specified in 3(a) for the final crack length
1b	1-IDF 60 Min.	Damage[7] due to 1 DSG	Damage[7] due to 60 minute diversion with an IDF = 1.0	2 times the total damage[7] due to the well phase and windmill phase,[3] ≤1.0	MQF[5] grown for 1 DSG	Additional crack growth due to a 60 minute diversion with an IDF = 1.0	Positive M.S. wrt residual strength due to the limit loads specified in 3(a) for the final crack length

Notes:
1 The analysis method that may be used is defined in section 4.0.
2 Load spectrum to be used for the analysis is the same load spectrum qualified for use in showing compliance to FAR(JAR) 25.571 augmented with windmilling loads as appropriate.
3 Windmilling phase is to be demonstrated following application of well phase spectrum loads.
4 The initial flaw for damage tolerance analysis of the windmilling phase need not be greater than the flaw size determined as the detectable flaw size plus growth under well phase spectrum loads for one inspection period for mandated inspections.
5 MQF is the manufacturing quality flaw associated with 95,95 probability of existence.(Reference - 'Verification of Methods For Damage Tolerance Evaluation of Aircraft Structures to FAA Requirements', Tom Swift FAA, 12th International Committee on Aeronautical Fatigue, 25 May 1983, Figures 42, and 43)
6 Maximum diversion time for Condition 1a is the maximum diversion time established for the airplane, not to exceed 180 minutes.
7. The allowable cycles to failure may be used in the damage calculation where DSG equals Design Service Goal.

(b)   Damage Tolerance Analysis

Where a damage tolerance analysis is used for substantiation the airplane should be shown to have adequate residual strength. The extent of damage for residual strength should be established taking into account growth from an initial flaw during the well phase followed by growth during the windmilling phase. The analysis should be conducted considering the following:

(i)   The size of the initial flaw should be equivalent to a manufacturing quality flaw associated with a 95% probability of existence with 95% confidence (95/95).

(ii)   For the well phase, crack growth should be calculated starting from the initial flaw defined in 4(b)(i) using an approved load spectrum (such as used in satisfying the requirements of FAR(JAR) 25.571)) for the duration specified in Table 4.1. Average material properties may be used.

(iii)   For the windmilling phase, crack growth should be calculated for the diversion profile starting from the crack length calculated in 4(b)(ii) using a mission that envelopes the AFM recommended operation accounting for transient exposure to peak vibrations as well as the more sustained exposures to vibrations (Ref. 2(a) through 2(d)). Average material properties may be used.

(iv)   The residual strength for the structure with damage equal to the crack length calculated in 4(b)(iii) should be shown capable of sustaining the combined loading conditions defined in 3(a) of this section with a factor of safety of 1.0.

5. Objective of Analysis

The airplane response analysis for engine windmill imbalance is a structural dynamic problem. The task is to develop acceptable analysis methodology for conducting dynamic investigations of imbalance events. The task further requires that the proposed methodology be validated. The objectives of the analysis methodology are to obtain representative or conservative airplane response characteristics. The goal of the windmilling analysis is to produce loads and accelerations suitable for the following evaluations:

(1) Structural

(2) Systems

(3) Flight deck and human factors

The analytical model should be valid to the highest windmilling frequency expected. The validation of the analytical model discussed in subsequent sections of this report will address the following aspects:

(1) Modeling details necessary to represent airframe structural dynamic characteristics

(2) Engine model detail for the windmilling engine

(3) Aerodynamic representation

The normal output of the windmilling analysis would be expected to yield loads and accelerations for all parts of the primary structure. The evaluation of equipment and human factors may require additional analysis or test. For example, the analysis may need to produce floor vibration levels, and the human factors evaluation may require a test where the seat and the human subject is subjected to floor vibration.

5. Loss Of Centerline Analysis

The above recommendations pertain to sustained imbalance due to fan blade loss and do not include loss of centerline support events except those that are designed to occur as an intentional result of the fan blade loss event. The following approach is recommended to address the loss of centerline condition with no fan blade loss.

Once the fan blade loss windmilling loads are determined, the design should be evaluated to determine if a loss of centerline event produces a more severe dynamic condition to the airplane. If the dynamic loads are greater for the loss of centerline event than those resulting from the fan blade loss imbalance in the windmilling range they should be evaluated as a design condition for the airplane in a manner approved by the authorities.

To evaluate the loss of centerline condition, the low pressure (LP) rotor system should be analyzed with each bearing removed, one at a time, with the imbalance consistent with the airborne vibration monitor (AVM) advisory level.

The windmilling analysis should account for secondary damage occurring during rundown from the maximum LP rotor speed (assumed centerline support loss speed).

windmilling frequencies. More detailed finite element modeling of the airframe is also acceptable.

Structural damping used in the windmilling analysis may be based on Ground Vibration Test (GVT) measured damping.

Engine Structural Model

The engine structural model consists of the engine, strut, and nacelle. Engine and nacelle models at the same level of detail as the models used for FAR §33.94 test simulation are acceptable for windmilling analysis. Optionally, a simplified engine model may be used in the windmilling analysis if shown to be valid. Engine models typically include the following:

(1)   Structural mass distribution and stiffness of static components

(2)   Each major rotor mass and rotor stiffness

(3)   Each shaft support

(4)   Engine mounts and additional load paths

(5)   Strut

The airplane model should use the modes and frequencies in the windmilling range extracted from the engine model described above. The engine subjected to the imbalance forces is recommended to be modeled in this level of detail.

Undamaged engines that are operating normally need only be modeled to represent their sympathetic response to the airplane windmilling conditions.

6.   Integrated Model

Airplane dynamic responses should be calculated with a complete integrated airframe and engine analytical model. The airplane model should be to a similar level of detail to that used for certification flutter and dynamic gust analyses, except that it must also be capable of representing asymmetric responses. The dynamic model used for windmilling analyses should be representative of the airplane to the highest windmilling frequency expected. The integrated dynamic model consists of the following components:

(1)   Structural Model
   (A)   Airframe
   (B)   Engine

(2)   Control System Model

(3)   Aerodynamic Model

(4)   Forcing Function

(5)   Gyroscopics

In the following sections of this chapter, the recommended level of model details are presented. These model parameters have been selected using ground and flight test based validation experience. In subsequent chapters, the test data is compared with analysis results to demonstrate the validation. Most of the test data utilized for this purpose are presently performed to satisfy various requirements of 14 CFR.

Airframe Structural Model

The structural model should include the mass, stiffness, and damping of the complete airframe. A lumped mass and finite element beam representation is recommended to model the airframe. This type of modeling represents each airframe component, such as fuselage, empennage and wings, as distributed lumped masses rigidly connected to weightless finite element beams that incorporate the stiffness properties of the component. Appropriate detail should be included to ensure fidelity of the model at

7. Airframe Structural Model

An analytical model of the airframe is required to calculate the response at any point on the airframe due to the rotating imbalance of a windmilling engine that has lost some portion of its fan blades. The airframe manufacturers currently use a reduced lumped mass finite element analytical model of the airframe for certification of aeroelastic stability (flutter) and dynamic loads including gust and dynamic landing. A typical model as shown in Figure 7.1 consists of a relatively few lumped masses connected by massless beams. As stated previously in Chapter 6, a full airplane model capable of representing asymmetric responses is necessary for windmilling.

Windmilling, dynamic gust, and landing analyses are based on calculating the dynamic response of the airframe due to a force input. The windmilling analysis should require calculating the response of the airframe at higher frequencies than are usually required to obtain accurate results for the other analyses mentioned above. Flutter analyses normally include frequencies exceeding the nominal engine windmilling frequencies.

In order to verify that the lumped mass model of the airframe gives an accurate representation of the response of the airframe in the windmilling range a comparison was made between analysis and test data for representative commercial airplanes. Six airframe manufacturers submitted data comparing analysis modal frequencies to measured Ground Vibration Test (GVT) frequencies for eighteen different airplanes. These airplanes included two, three, and four engine airplanes with wing, fuselage, and tail mounted engines. A sample of the data submitted, as shown in Figure 7.2, define the airplane and the typical engine fan windmilling frequencies. Also included is a description of each of the natural modes of the airplane along with their test frequency, analysis frequency, percent difference, and test damping.

Control System Model

The automatic flight control system should be included in the analysis unless it can be shown to have an insignificant effect on the airplane response due to engine imbalance.

Aerodynamic Model

The use of unsteady three-dimensional panel theory methods for incompressible or compressible flow, as appropriate, is recommended for modeling of the windmilling event. Interaction between aerodynamic surfaces and main surface aerodynamic loading due to control surface deflection should be considered where significant. The level of detail of the aerodynamic model should be supported by tests or previous experience with applications to similar configurations. Main and control surface aerodynamic data are commonly adjusted by weighting factors in the aeroelastic response solutions. The weighting factor for steady flow (k=0) are usually obtained by comparing wind tunnel test results with theoretical data.

Forcing Function and Gyroscopics

Engine gyroscopic forces and imbalance forcing function inputs should be considered. The forcing function should be calibrated to the results of test performed under Sec. 33.94 of 14 CFR.
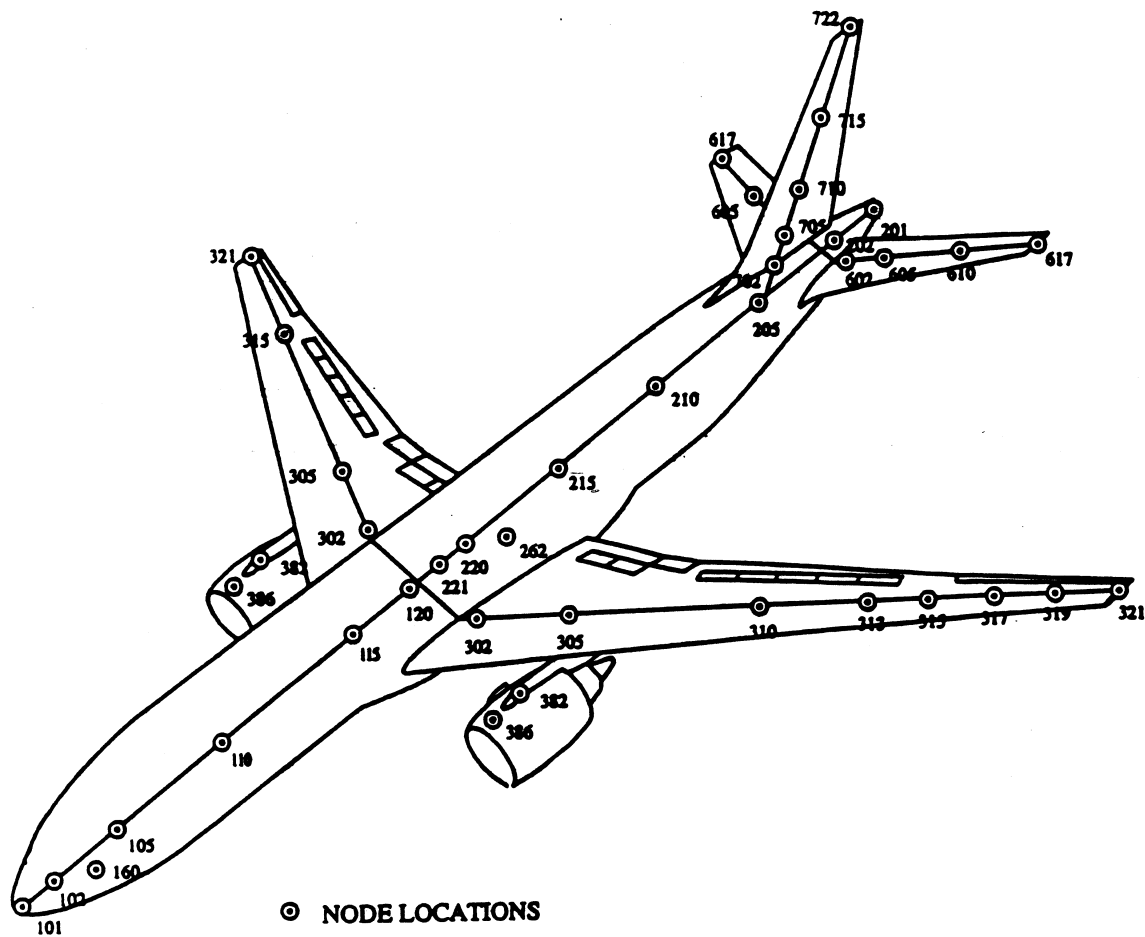
Figure 7.1 Typical Airframe Structural Model

A plot of the analysis frequencies versus the GVT frequencies is shown in Figure 7.3 and a plot of the difference of analysis and GVT is shown in Figure 7.4. Most of the typical windmilling frequencies reported are within the range from 15 to 25 hertz. Figure 7.3 and 7.4 indicate that the analytical model is as accurate for the windmilling range as for lower frequencies. The histogram in Figure 7.5 shows that for all the reported data the vast majority of differences are within ± 10%, which is considered adequate for windmilling analysis.

Structural damping used in the windmilling analysis may be based on Ground Vibration Test (GVT) measured damping.

A lumped mass beam model is currently accepted for certification analysis including: dynamic gust, dynamic landing, and flutter. The measured GVT data has validated the analytical model through the windmilling range. Therefore, a lumped mass beam model of the airframe is acceptable for frequency response analyses due to engine fan blade loss windmilling. Additional detail may be needed to insure adequate fidelity for windmilling frequencies. Finite element models should be used as necessary.
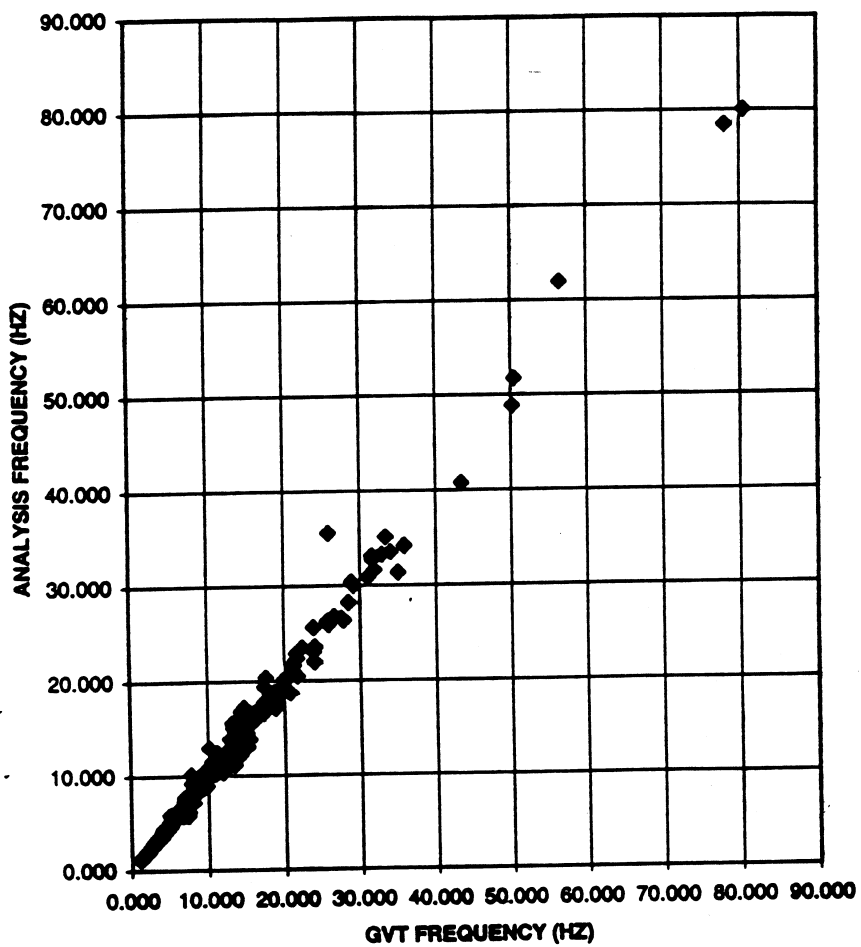
ANALYSIS VS GVT FREQUENCY

Figure 7.3

Modal Frequencies Comparison

(WINDMILLING FREQUENCY: TYPICAL=20 HZ.)

DESCRIPTION	GVT FREQUENCY (HZ)	ANALYSIS FREQUENCY (HZ)	DIFFERENCE (%)	TEST DAMPING (%critical)
SYMMETRIC:				
RIGID BODY PITCH	0.27	0.279	3.33	
RIGID BODY FORE & AFT	0.78	0.825	5.77	
RIGID BODY PLUNGE	1.6	1.54	-3.75	1.48%
WING 1ST BENDING	1.79	1.759	-1.73	0.45%
WING ENGINE YAW	2.07	2.097	1.30	1.72%
FUSE BEND / WENG PITCH	3.22	3.204	-0.50	0.62%
WING INNER PANEL TORSION	4.1	4.117	0.41	0.69%
AFT ENGINE PITCH	4.8	4.775	-0.52	0.30%
HORIZ STAB 1ST BENDING	5.39	5.565	3.25	0.52%
WING 2ND BENDING	5.5	5.225	-5.00	
WING 1ST FORE & AFT	6.01	6.09	1.33	0.96%
WING ENGINE ROLL	6.48	6.509	0.45	0.78%
WING 3RD BENDING	8.81	8.459	-3.98	
MAIN LANDING GEAR YAW	9.62	9.618	-0.02	2.04%
WING 2ND TORSION	11.87	11.187	-5.75	2.22%
WING OUTER PANEL TORSION	12.5	12.497	-0.02	1.76%
HORIZ STAB 1ST FORE & AFT	14.4	14.432	0.22	1.41%
VERT STAB 1ST FORE & AFT	15.75	15.763	0.08	
HORIZ STAB 2ND BENDING	17.19	17.381	1.11	
HORIZ STAB 1ST TORSION	25.69	26.295	2.36	
ANTI-SYMMETRIC:				
RIGID BODY YAW	0.43	0.408	-5.12	
RIGID BODY LATERAL	0.89	0.769	-13.60	
RIGID BODY ROLL	1.29	1.306	1.24	1.04%
WING 1ST BENDING	2.13	2.129	-0.05	0.81%
WING ENGINE YAW	2.35	2.385	1.49	1.27%
FUSE/WING/VS CPLD	2.78	2.698	-2.95	0.43%
VERT STAB 1ST BENDING	3.95	3.667	-7.16	0.57%
WING ENGINE PITCH	4.15	4.005	-3.49	0.49%
HORIZ STAB 1ST BENDING	4.5	4.235	-5.89	0.82%
FWD FUSE BEND/WG F & A	4.95	4.97	0.40	0.57%
AFT ENGINE ROLL	5.57	5.506	-1.15	1.32%
WING ENGINE ROLL	6.37	6.481	1.74	0.88%
WING 2ND BENDING	7.16	6.656	-7.04	1.48%
HORIZ STAB YAW	7.36	7.279	-1.10	0.99%
MAIN LANDING GEAR CPLD	8.32	8.662	4.11	2.78%
VERT STAB 2ND BENDING	8.76	9.267	5.79	1.38%
MAIN LANDING GEAR YAW	9.94	10.065	1.26	
WING OUTER PANEL TORSION	11.66	11.84	1.54	
HORIZ STAB 2ND BENDING	15.41	16.681	8.25	
UPPER WINGLET 1ST BENDING	21.59	22.922	6.17	
HORIZ STAB 1ST TORSION	25.69	26.154	1.81	
WING 3RD BENDING				

Figure 7.2

DISTRIBUTION DIFFERENCE
ANALYSIS VS GVT

Figure 7.5

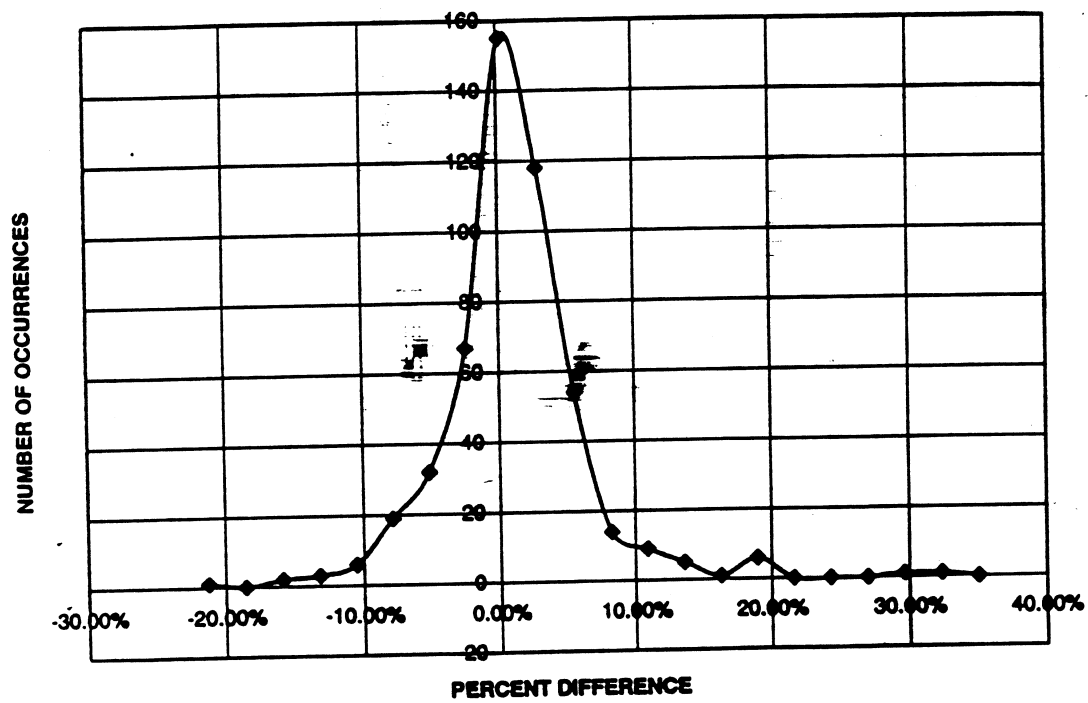**ANALYSIS VS GVT FREQUENCY**

Figure 7.4

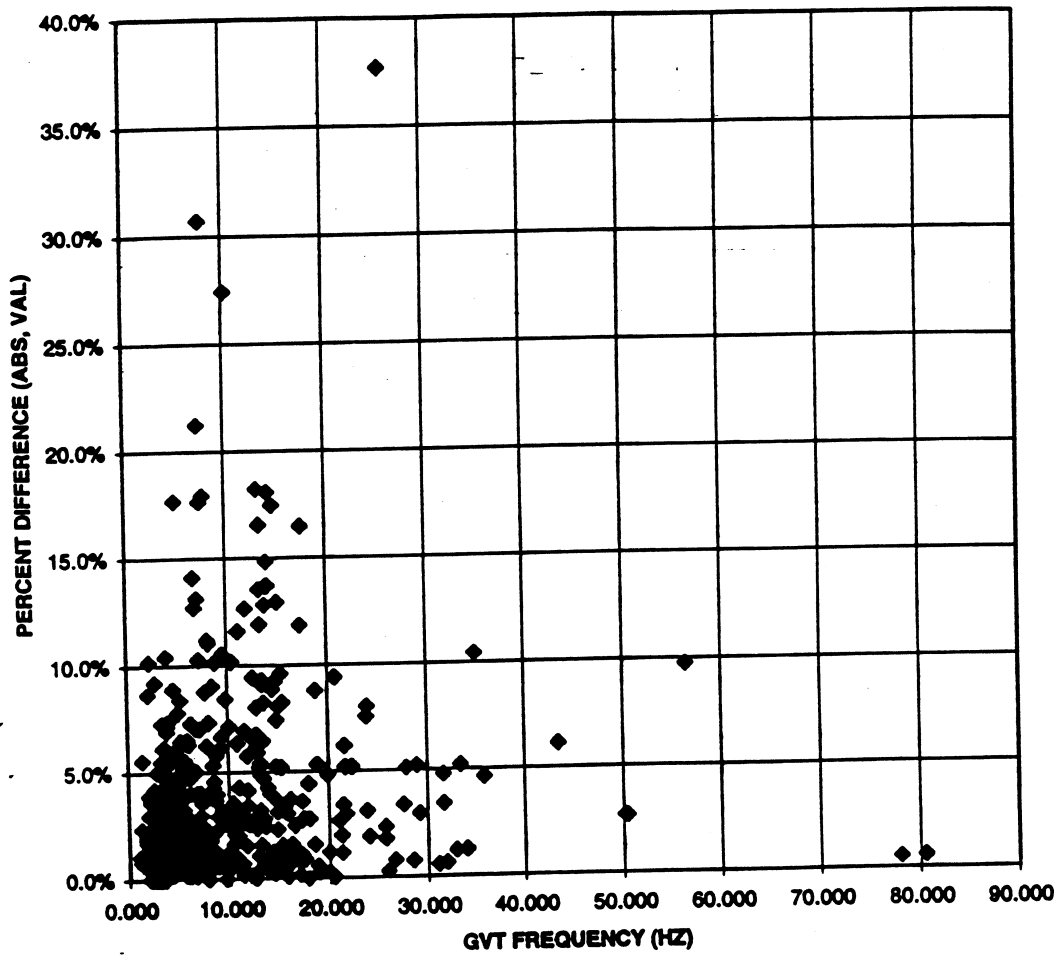(Y-axis: PERCENT DIFFERENCE (ABS, VAL))
(X-axis: GVT FREQUENCY (HZ))

Features modeled specifically for blade loss windmilling analysis typically include fan imbalance, component failure and wear, rubs, (blade to casing, and intershaft), and resulting stiffness changes. Manufacturers whose engines fail the rotor support structure by design during the blade loss event should also evaluate the effect of the loss of support on engine structural response during windmilling.

Features which should be modeled specifically for loss of centerline windmilling events include the effects of gravity, inlet steady air loads, rotor to stator structure friction and gaps, and rotor eccentricity. Secondary damage, such as additional mass loss, overload of other bearings, permanent shaft deformation, or other structural changes affecting the system dynamics, occurring during rundown from maximum LP rotor speed and subsequent windmilling should be accounted for.
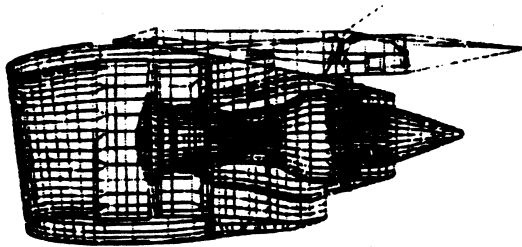
The definition of the model should be mutually agreed upon between the airframe and engine manufacturers based on test and experience. The model is validated based on dedicated vibration tests and results of FAR 33.94 fan blade loss test. In cases where compliance to FAR 33.94 is granted by similarity instead of test, the windmill model should be correlated to prior experience.

Validation of the engine model static structure including the strut is achieved by a combination of engine and component tests which include structural tests on major load path components. The adequacy of the engine model to predict rotor critical speeds and forced response behavior is verified by measuring engine vibratory response when imbalances are added to the fan, LPC (or IPC), HPC, HPT, (IPT if for a three shaft engine) and LPT rotors . Vibration data are routinely monitored on a number of engines during the engine development cycle, thereby providing a solid basis for model correlation.

8. Engine Structural Model

The purpose of this chapter is the definition of an engine structural model which adequately describes the dynamic characteristics needed to accomplish the objectives of the windmilling loads analysis.

Engine manufacturers construct various types of dynamic models to determine loads and to perform dynamic analyses on the engine rotating components, its static structures, mounts and nacelle components. Dynamic engine models can range from a centerline two-dimensional (2D) model , to a centerline model with appropriate three-dimensional (3D) features such as mount and strut, up to a full 3D finite element model (3D FEM). Any of these models can be run for either transient or steady state conditions. A typical 3D FEM engine model is shown in Figure 8.1.

Figure 8.1 Typical Engine

These models typically include all major components of the propulsion system, such as the nacelle intake, fan cowl doors, thrust reverser, common nozzle assembly, all structural casings, frames, bearing housings, rotors and a representative strut. Gyroscopic effects are included. The models provide for representative connections at the engine-to-pylon interfaces as well as all interfaces between components (e.g., inlet-to-engine and engine-to-thrust reverser).

9.   Aerodynamic Model

The airframe manufacturers currently use an aerodynamic model of their airframes for calculation of dynamic gust loads and flutter analyses that generally covers all of the significant frequencies required for windmilling analyses.

Flight test results have been collected by the aircraft manufacturers in order to provide a basis for validation of aerodynamic forces which will be used for dynamic analysis in windmilling conditions. Available flight test data for control surface sweep inputs were reviewed indicating good correlation between calculated and measured response. Figures 9.1 through 9.3 are representative results showing the response of the fuselage due to aileron, elevator, and rudder sweep inputs respectively. All the comparisons of analysis predictions versus flight test data showed good correlation up to approximately 8Hz. Reliable flight test data above 8Hz is difficult to obtain with control surface sweeps since the actuators roll off at these frequencies giving a low signal versus noise ratio.

The airframe manufacturers have evaluated the sensitivity of the windmilling analysis to the accuracy of the unsteady aerodynamic model. Responses at several different locations on the airplane were calculated for an engine fan imbalance at frequencies from zero through the maximum expected windmilling frequency. The airplane configurations analyzed consisted of a wing mounted twin, a wing mounted four engine airplane, and a fuselage mounted twin. The frequency response analyses were performed for the following aerodynamic variations:

(1)   Nominal aerodynamics.

(2)   ±10% applied to all unsteady aerodynamic forces.

(3)   ±20% applied to nacelle unsteady aerodynamic forces.

While the validation aspects listed above are important for representation of the windmilling loads, the fan blade loss correlation is also pertinent to the windmill event because the event involves predicting the response of the entire propulsion system under a high level imbalance load. Correlation of the model against the FAR 33.94 fan blade loss engine test is a demonstration that the model accurately predicts initial blade release event loads, any rundown resonant response behavior, frequencies, potential structural failure sequences, and general engine movements and displacements. To enable this correlation to be performed, instrumentation of the blade loss engine test is used, for example high speed cine and video cameras, accelerometers, strain gauges, continuity wires, and shaft speed tachometers.

wing and stabilizer vanes are sometimes used to excite the aeroelastic modes of the airplane at frequencies up to 30 Hz. These tests have shown that analytically predicted stability characteristics are acceptable for all significant structural modes.

Flight flutter tests demonstrate that currently employed aerodynamic modeling is reliable for frequencies of windmilling. These methods are accepted for certification flutter analyses that are more sensitive to aerodynamic variations than airplane response due to windmilling imbalance. Aerodynamic forces are well behaved and are continuous functions in the flight regime involved in windmilling diversions (subsonic and low transonic).

Figure 9.4 is a plot of the acceleration response of the cockpit versus frequency for one of the airplanes analyzed with the aerodynamic variations listed above. The small magnitude of differences shown in the Figure is representative of all of the results reviewed. This magnitude of difference indicates that the engine imbalance response analyses are not sensitive to reasonable variation in aerodynamics.

Analyses were also performed with no aerodynamics and the results indicated in general a significant effect on the response of the airplane. The analysis with no aerodynamics was generally conservative at most frequencies, but not always.

Validation of Aerodynamic Model

Available flight test data covers frequencies up to 8Hz. In this range of frequencies, flight test and analysis shows good agreement. Flight flutter tests demonstrate that currently employed aerodynamic modeling is reliable for frequencies within the windmilling range. These methods are accepted for flutter analysis which is more sensitive to aerodynamic variation than response to windmilling imbalance.

Generalized aerodynamic forces for all modes up through the windmilling range behave smoothly and do not exhibit large variations versus reduced frequencies in the flight regime (subsonic and low transonic) involved in windmilling diversions. Based on the above observations, it is concluded that aerodynamic modeling currently used in certification flutter analyses is adequate for windmilling analysis.

Generally, airplane response data from flight test shows good correlation compared to analysis up to approximately 8 Hz. Correlated analysis to test data generally are not available above 8 Hz. Airplane response data are usually obtained by control surface sweep inputs. These data are normally limited to approximately 8 Hz because of the frequency response characteristics of the control surface actuators, which are incapable of exciting the airplane at higher frequencies. During flight flutter testing,

Flight Test vs Analysis
Fuselage Response due to Elevator Sweeps
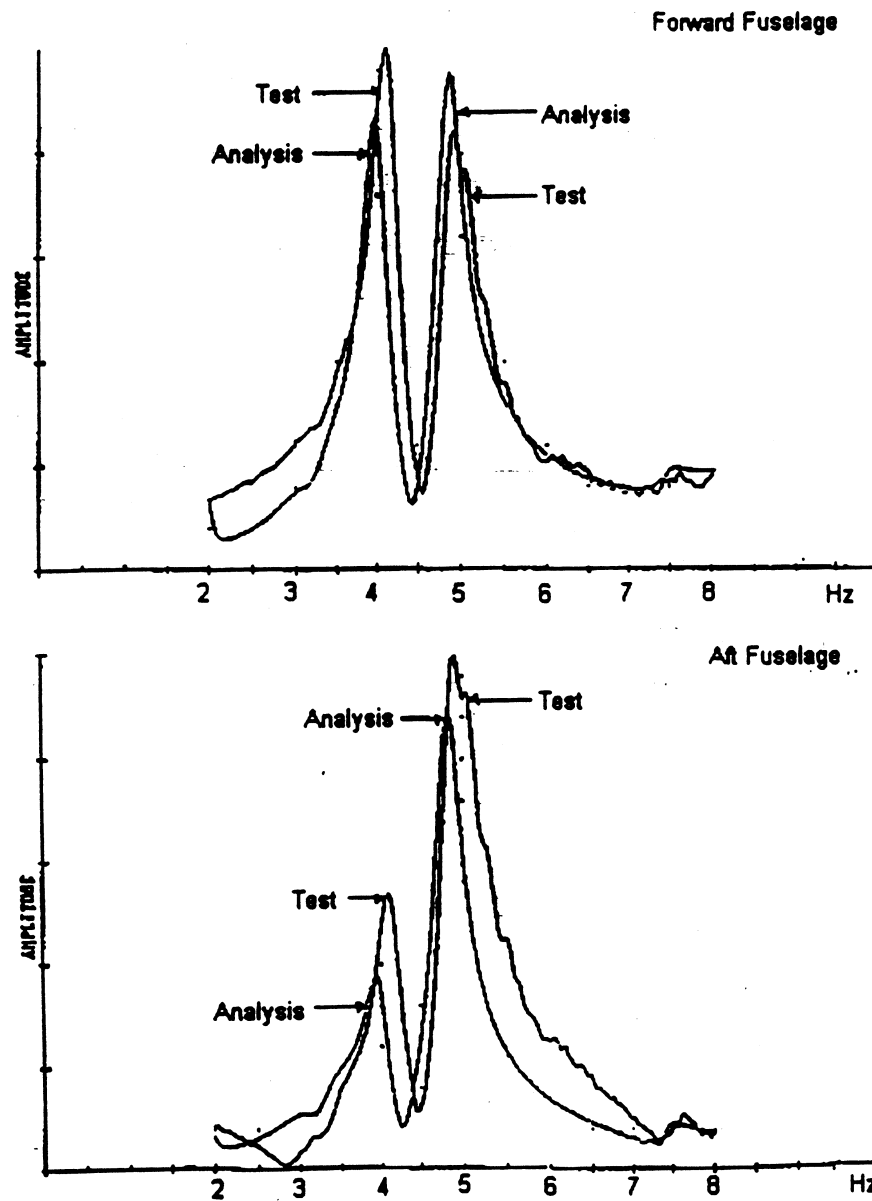
Figure 9.2

Flight Test vs Analysis
Fuselage Response due to Aileron Sweeps
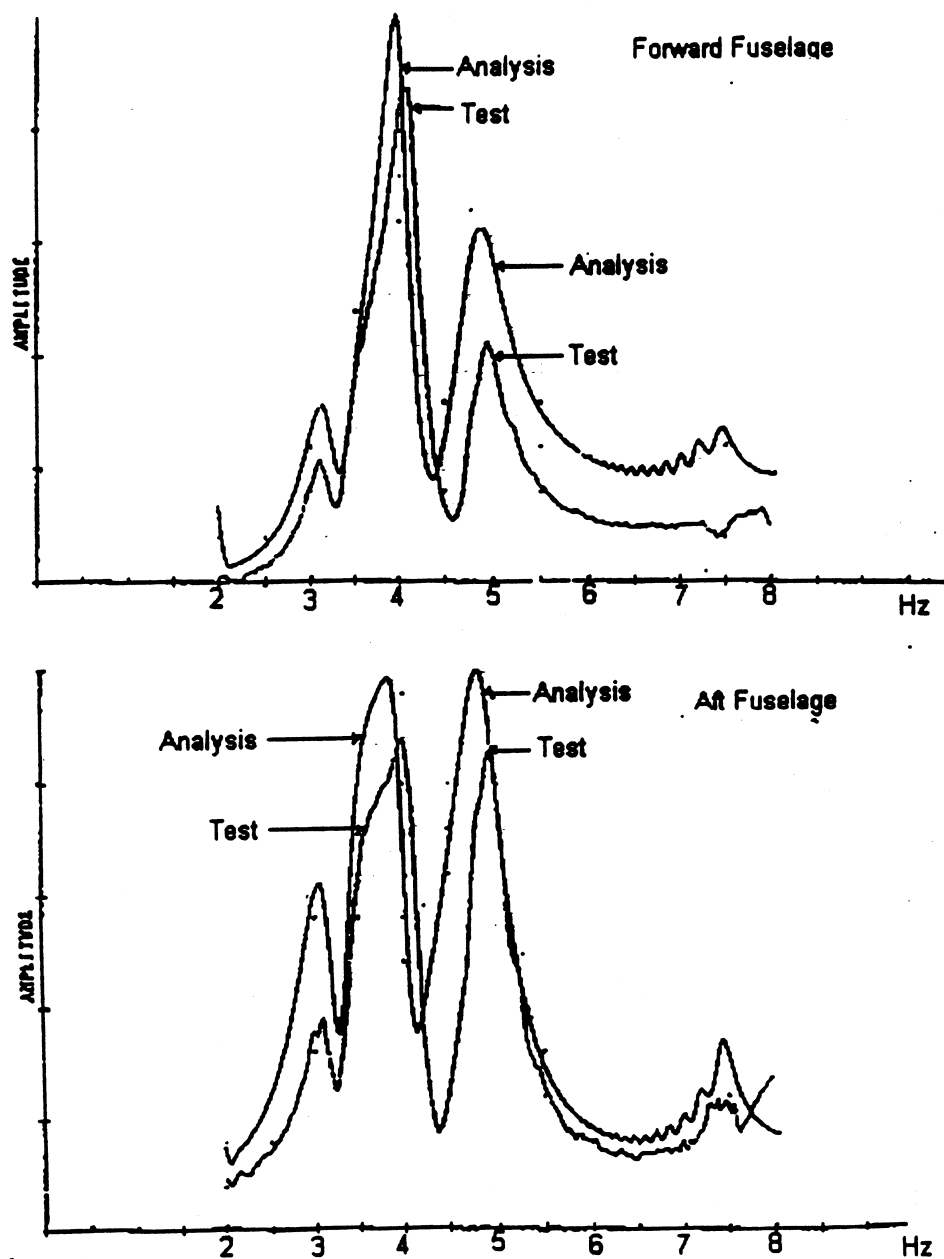
Figure 9.1

FREQUENCY RESPONSE DUE TO ENGINE BLADE LOSS
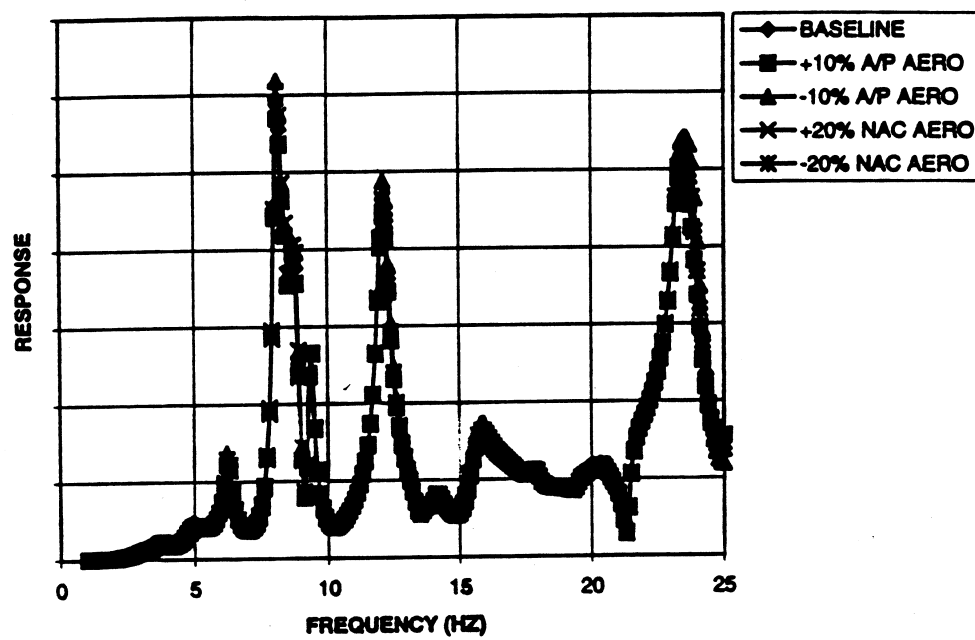
Figure 9.4

Flight Test vs Analysis
Fuselage Response due to Rudder Sweeps
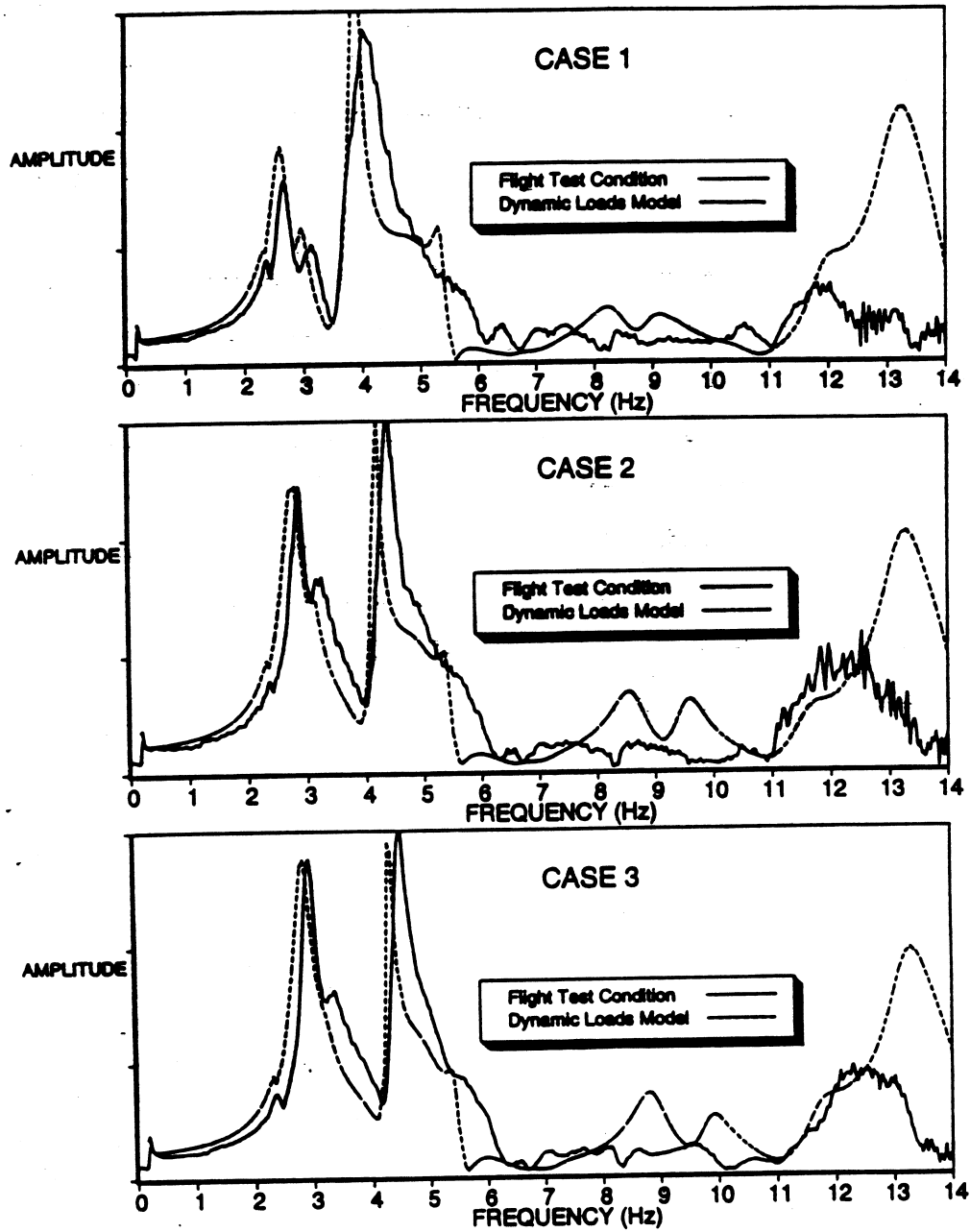
Figure 9.3

to completely identify all of the aircraft modes necessary for windmilling analysis, multiple shaker locations are needed, including locations on the engine.

The dynamic behavior of the whole airplane in the structural frequency range associated with windmilling is normally validated by the flight flutter tests performed under 25.629 14 CFR. Some typical results are presented in Chapter 9.

10. Validation of Integrated Model

The model parameters recommended in Chapter 6 are based on analysis methods that are well understood and represent present industry practice for demonstrating compliance with various sections of 14 CFR. The analysis techniques have a long history of ground and flight test based validation.

The airframe model is validated by ground vibration tests that typically consist of a complete airframe and engine configuration subjected to vibratory forces imparted by electro-dynamic shakers. Although the forces applied are small compared to windmilling forces, these tests yield reliable dynamic characteristics (structural modes) of the airframe engine combination. Structural damping values obtained in these tests are conservative for application to windmill analysis. Application of higher values of damping appropriate for the larger amplitudes on the windmill analysis, need to be justified.

These characteristics are valid within the linear range of structural material properties. The windmilling forces, though greater than test shaker forces, are far less than forces required to induce nonlinear behavior of the structural material; i.e. yielding. Thus, a structural dynamic model that is validated by ground vibration test is considered appropriate for the windmilling analysis.

However, the ground vibration test of the aircraft does not necessarily provide sufficient information to assure that the transfer of the windmilling imbalance loads from engine is correctly accounted for as described in Chapter 8. The load transfer characteristics of the engine to airframe interface via the strut should be validated by test and analysis correlation. In particular, the effect of the point of application of the load on the dynamic characteristics of the integrated model needs to be understood. To this end, the modes and frequencies of several airplanes have been determined by tests where the point of application of the loads is changed; e.g., at the wing, at the fuselage, tail surfaces, and at the engine. The results are presented in Tables 10.1 to 10.3 . The results show that

Table 10.2
GVT Multiple Shaker Configurations
Test Frequencies and Modeshapes

Mode Description	Run 2	Run 4	Run 6
Rigid Body Yaw	0.389	0.379	0.379
Rigid Body Lat Trans w/Roll	0.451	0.452	0.453
Rigid Body F/A Trans w/Pitch	0.548	0.546	0.552
Rigid Body Roll	0.713	0.712	0.717
Rigid Body Pitch w/Roll	0.783	0.779	0.788
Rigid Body Vert Trans w/Roll	0.970	0.968	0.975
Sym 1st Wing Vert Bend	1.620	1.622	1.620
Antisym 1st Wing Vert Bend	2.008	2.010	2.009
Sym Nac SB	2.479	2.370	2.224
Antisym Nac SB	2.666	2.623	2.613
Antisym Aft Body Tor/Wing VB	2.981	2.979	2.985
Sym Wing VB/Nac VB/Body VB	3.005	3.042	3.028
Antisym Wing VB/H Stab Opp Phase/Body Tor/Nac VB	3.319	3.316	3.316
Sym Wing VB/Nac VB/Body VB	3.404	3.405	3.406
Antisym Wing VB/Body Tor/Nac VB	3.661	3.642	3.705
Antisym H Stab Roll	3.794	3.817	3.862
Sym Wing VB/Stab VB Opp Phase	4.089	4.090	4.127
Antisym Wing VB/Stab VB in Phase/Fin B	4.269	4.263	4.296
Sym Wing VB/Antisym Stab VB/Fin B	4.343	4.340	4.376
Sym Wing VB/Stab VB Opp Phase/Fin LB/NLG Lat	4.528	4.436	4.446
Sym Wing VB/Fin LB		4.531	4.550
Sym Wing VB/Fin LB(Fin & Stab Phase Change)	4.578		4.580
Antisym Wing VB/Stab VB Opp Phase/Fin LB/NLG Lat/Body LB	4.964	4.921	4.921
Sym Stab VB/Antisym Wing CW	5.159	5.129	5.126
Sym Stab VB/Sym Wing VB	5.182	5.165	5.205
NLG Lat/Antisym Wing VB/Antisym Stab CW	5.557	5.586	5.594
Sym Wing CW	5.621	5.616	5.631
Sym Wing CW	5.723	5.710	5.739
Antisym Wing VB/Nonsym H Stab/Fin LB	5.939	5.997	6.011
Sym Wing VB/Stab VB/Nac Tor RH Dominate/Fin CW	6.333	6.276	6.123
Antisym H Stab CW/Fin CW	6.422	6.406	6.638
LH Nac Tor	6.894	6.740	6.694
Antisym Wing VB/Stab CW/NLG FA/MLG FA	7.263	7.113	7.189
Antisym Wing/Stab CW/Fin & Body Lat	7.388	7.362	
Antisym Wing/Stab CW/MLG FA/Nac Tor/Body Lat	7.696	7.795	7.596
Nonsym Wing VB/Stab VB/MLG FA/Fin CW	8.113		
Sym Wing VB/MLG FA	8.244	8.243	8.250
Sym Wing VB/MLG FA/NLG FA/Fin CW	8.481	8.483	8.453
Antisym Wing CW/MLG FA/Sym H Stab VB/Body Tor	8.683		
Antisym Wing CW/H Stab CW Opp Phase/Fin LB/Body LB	8.902	8.917	8.945

Table 10.1
GVT Multiple Shaker Configurations

Run	Shaker Location (Direction)	Freq. Range (Hz)
1	Both wing tips vert, LH stab vert, fin lateral	0 to 6.25
2	Both wing tips vert, LH stab vert, fin lateral	0 to 25
3	LH wing vert, LH stab vert, both nacs lat	0 to 6.25
4	LH wing vert, LH stab vert, both nacs lat	0 to 25
5	Rudder, elevator, aileron	0 to 25
6	Left and right nac vertical and lateral	0 to 25

Table 10.3
GVT Multiple Shaker Positions
Analysis and Test Comparison

Anal. Freq. (Hz)	Mode No.	Test Freq. (Hz)	Damping g	Description	Run No.
1.65	1	1.62	0.007	Symmetric, 1st Wing Bending	1
2.04	2	2.01	0.006	Antisymmetric, 1st Wing Bending	1
2.45	3	2.32	0.041	Symmetric, Nacelle Lateral	3
2.60	4	2.65	0.022	Antisymmetric, Nacelle Lateral	1
2.90	5	2.98	0.011	Antisymmetric, 1st Body Lateral Bending/Aft body Torsion/2nd Wing Bending/1st Wing Chordwise	1 1
3.02	6	3.02	0.108	Symmetric, 1st Body Vertical Bending/Nacelle Vertical/2nd Wing Bending	1
3.33	7	3.31	0.013	Antisymmetric, Nacelle Vertical/Aft Body Torsion/2nd Wing Bending	1
3.34	8	3.40	0.018	Symmetric, Nacelle Vertical/2nd Wing Bending/1st Body Vertical Bending	1
	9	3.63	0.034	Antisymmetric, Main Gear+Platform Fore-Aft	1
3.84	10	3.78	0.024	Antisymmetric, Aft Body Torsion/1st Stabilizer Bending	1
4.36	11	4.08	0.028	Symmetric, Main Gear+Platform Lateral	1
4.33	12	4.26	0.023	Antisymmetric, 1st Fin Bending/2nd Wing Bending (Wing and Stab Tips in Phase)	1
4.44	13	4.33	0.022	Antisymmetric, 1st Fin Bending/2nd Wing Bending (Wing and Stab Tips Out of Phase)	1
	14	4.45	0.030	Antisymmetric, Nose Gear+Platform Lateral	6
5.04	15	4.51	0.028	Symmetric, 3rd Wing Bending	3
	16	4.98	0.048	Antisymmetric, Wing Chordwise/1st Body Lateral Bending/Nose Gear Lateral	1
	17	5.15	0.029	Antisymmetric, Main gear Lateral/Wing Chordwise	1
5.10	18	5.18	0.020	Symmetric, 1st Stab. Bending/1st Fin Chordwise	2
5.27	19	5.27	0.054	Antisymmetric, Wing Chordwise	5
5.53	20	5.56	0.017	Antisymmetric, 3rd Wing Bending/Stabilizer Chordwise/Nose Gear Lateral	2
5.57	21	5.72	0.025	Symmetric, Wing Chordwise/Fin Chordwise	2
6.92	22	6.01	0.038	Right Nacelle Torsion	6
6.18	23	6.41	0.046	Antisymmetric, Stabilizer Chordwise/Body Ovalizing	4

Table 10.2 (continued)
AIRPLANE GVT MODESHAPES AND FREQUENCIES (HZ)
PRELIMINARY TEST FREQUENCIES

Mode Description	Run 2	Run 4	Run 6
Nonsym Wing VB/Antisym Wing CW/Stab CW Opp Phase/Fin LB	9.134	9.121	9.171
Antisym Wing VB/Sym H Stab VB Opp Phase/Fin CW/Body VB	9.229	9.371	
Antisym Wing VB/Stab CW/Body Tor	9.511	9.501	9.536
Antisym Wing VB/H Stab VB/Fin LB/Body Tor	10.250		
Antisym Wing VB/H Stab VB/Fin LB/Body Tor	10.269		10.190
Sym Wing VB/H Stab VB in/Body VB	10.325	10.322	10.369
Sym Wing Tor+VB/H Stab VB Opp/Body VB —	10.773	10.776	
Sym Wing VB/H Stab VB Opp/Body VB	10.840		
Antisym Wing CW/H Stab CW in Phase/Fin LB/Body LB			10.919
Antisym Wing Tor/H Stab VB/Fin Rudder LB/MLG L	11.282	11.294	11.195
Antisym Wing VB/H Stab VB/Fin LB		11.348	11.348
Antisym Wing VB/H Stab VB/Fin LB Opp Phase			11.445
Sym Wing VB/Nonsym H Stab VB/Fin Rudder LB	11.874		
Antisym Wing Tor/H Stab VB/Fin Rudder LB/F Body L	12.063	12.055	12.077
Antisym Wing Tor/H Stab VB/Fin Rudder LB	12.081		
H Stab Elev/Fin Rudder 2nd VB	12.598		
Sym Wing VB/Nonsym H Stab VB	12.671	12.611	
Sym Wing VB/Nonsym H Stab VB/Rud&Fin LB	12.730	12.801	
Sym Wing Tor/Asym H Stab&Elev VB & Rot/Rud&Fin LB	13.341		12.993
Sym Wing Tor/Antisym H Stab VB/Rud&Fin LB	13.376	13.694	13.526
Antisym Wing Tor/H Stab VB/Fin Rudder LB			14.027
LH Asym Elev Rot	14.215	14.477	
Sym Wing Tor/Asym H Stab&Elev VB & Rot/Rud&Fin LB			14.667
Antisym Wing VB/LH Stab VB/Elev Rot/Rud&Fin LB	14.638		
Antisym Wing VB/Fin Rudder LB/L H Stab Tor/R H Stab VB	14.725		
Sym Wing Tor+VB/H Stab VB Opp/Body VB			14.870
Asym Wing VB RH Dominate/Sym H Stab&Elev VB/Rudder LB	15.054		
Sym Wing CW/Nac Tor/Rudder Opp Fin LB			15.343
Asym Wing VB -90LH to RH	15.955	15.967	15.715
Sym Wing Tip VB	16.033		
Antisym Wing Tip VB	16.044	16.492	16.283
Antisym Wing VB/H Stab Tor/Rudder LB	16.539	16.563	16.593
Antisym Wing Tip VB/Fin&Rudder LB/Rud-Tab Rot/H Stab in Phase w/Wing		16.613	
LH Elev Tor	18.156		
Antisym Wing Tor/H Stab VB/Rudder LB	18.882	18.779	18.950
Antisym Wing Tip VB/Fin&Rudder LB/Rud-Tab Rot/H Stab Opp Phase w/Wing			19.075
Antisym Wing Tip VB/Nac LB/Rudder Tor/H Stab Opp Phase w/Wing			19.601
Sym Wing Tip Tor	19.931		
Sym Wing Tip Tor/H Stab Tip VB/Elev Tor	20.030	20.014	
Antisym Wing Tip VB/H Stab VB/Rudder Bending	20.314		
H Stab Tip VB/Elev Tor	20.647	20.538	
Fin Tip LB/Rudder Tor/Rud-Tab Rot	22.861		20.953
Asym Wing Tip Tor CW/Nac Diag @ 45/Rudder Tor			21.194
Antisym Wing Tip VB/Rudder Tor/Rud-Tab Rot	24.121		

11. CONCLUSIONS AND RECOMMENDATIONS

This report is submitted to complete the task published in the Federal Register (Vol. 61, Number 129) on July 3, 1996 and assigned to the Aviation Rulemaking Advisory Committee (ARAC) entitled "Engine Windmilling Imbalance Loads." This report details the work performed in establishing an acceptable criteria and methodology for determining the dynamic airplane loads and accelerations resulting from an imbalanced windmilling engine. It addresses fan blade failure events as well as other likely causes of significant engine vibratory loads such as loss of centerline support.

The service history data of high by-pass ratio engines under windmilling imbalance condition was reviewed. The review concluded that current airplanes have demonstrated adequate capability to withstand loss of fan blade and loss of centerline support. However, this may not always be the case, especially if new airplane and engine designs are significantly different from past conventional configurations. An examination of the existing criteria did not identify any specific requirements that would continue to guarantee the positive outcome experienced in the known events. Therefore, the working group developed recommended criteria to be used in assuring safety of flight in all future airplanes in the event of windmilling under engine imbalance. These criteria include the windmilling condition definition which should be used in evaluating structure, systems including operating engine(s), and flight crew performance. Specific criteria for evaluating structure have been developed.

The criteria recommended in this report are applicable to high bypass ratio engines with fan diameters greater than 60 inches. In the absence of evidence justifying an alternative approach providing an equivalent level of safety, these criteria should also be assumed to apply equally to airplanes with smaller diameter engines.

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Anal. Freq. (Hz)	Mode No.	Test Freq. (Hz)	Damping g	Description	Run No.
	24	6.64	0.023	Fin Chordwise	6
6.94	25	6.69	0.038	Left Nacelle Torsion	6
6.33	26	7.36	0.040	Antisymmetric, Body Ovalizing/Body Roll/Stab. Chordwise/Nose Gear Lateral	4
	27	7.69	0.031	Antisymmetric, 3rd Wing Bending/Nacelle Vertical/Body Ovalizing/Main Gear Vertical	2
7.85	28	7.85	0.043	Symmetric, Nose Gear Vertical/Main Gear Fore-Aft/Fin Chordwise/Stabilizer 1st Bending/Nacelle Vertical/Body 1st Vertical Bending/Wing 3rd Bending	6
	29	8.24	0.023	Symmetric, 3rd Wing Bending/Main Gear Fore-aft	2
	30	8.68	0.023	Antisymmetric, Fore Body Ovalizing out of Phase with Aft Body Ovalizing/Wing 2nd Chordwise	2
8.80	31	8.90	0.022	Antisymmetric, Fore Body Ovalizing in Phase with Aft Body ovalizing/Body Roll/Main Gear Vertical/ Fin 1st Bending/Stabilizer 1st Bending/Stabilizer 1st Chordwise	2
	32	9.13	0.025	Antisymmetric, Aft Body Ovalizing in Phase with 1st Bending/Wing 2nd Chordwise out of Phase with Stabilizer 1st Chordwise/Stabilizer 1st Bending/Wing 3rd Bending/Main Gear Vertical	2
8.92	33	9.23	0.006	Symmetric, Body 2nd Vertical Bending/Fin Chordwise/Stabilizer 1st Bending/Nacelle Vertical Bending	2
9.81 9.85	34	9.51	0.035	Antisymmetric, Wing 3rd Bending/Fore Body Ovalizing in Phase with Aft Body Ovalizing/Wing 1st Chordwise out of Phase with Stabilizer Chordwise/Rudder Rotation	2 2
9.33	35	10.19	0.025	Symmetric, Wing 1st Torsion out of Phase Nacelle Vertical Bending/Wing 3rd Bending	6
	36	10.27	0.027	Antisymmetric, Aft Body Ovalizing out of Phase with Fin 1st Bending/Stabilizer 1st Bending/Wing 3rd Bending/Stabilizer Chordwise	2

The working group reviewed the traditional ground vibration tests, flight flutter tests, and tests performed under Sec. 33.94 of 14 CFR and concluded that no further demonstrative ground or flight test programs would be needed in order to achieve the objective of establishing confidence in the proposed methodology. However, it is recommended that the GVT conducted to validate the structural dynamic model should include multiple shaker locations, including locations on the engine.

The working group recommends that a harmonized FAR Part 25 Advisory Circular and an ACJ to JAR 25 be developed based on the technical information contained in this report.

For the blade loss event, design evaluation criteria for future airplanes have been developed and presented in Chapter 4. These establish the maximum level of engine imbalance and associated diversion times to be used for analytical determination of the airplane loads and accelerations. The maximum level of engine imbalance for blade loss is recommended to be 1.0 imbalance design fraction, which is the mass imbalance resulting from the FAR 33.94 blade containment and rotor imbalance test. The two recommended diversion times are 60 minutes and the maximum diversion time up to 180 minutes. In addition, an approach for evaluating the loss of centerline support condition has been recommended in Chapter 4.

Service experience indicates that engine rundowns occur at all levels of blade fraction. Engines which have experienced a full blade loss or more have always rundown to idle or below within a few seconds after blade release. All were shut down by the flight crew within a few seconds after rundown. Some events between 0.25 and less than 0.5 blade fraction may run on indefinitely unless the crew takes action to shut down the engine. These events cause higher frequency vibration than windmilling events but are concluded not to be a threat to the airplane structure. However, they have caused crew confusion as to which engine should be shut down. Consideration should be given to ensure that on future airplane designs the crew members are able to make the decision to shut down the appropriate engine in a timely manner.

Recommendations are included addressing the level of detail required for engine and airframe modelling to adequately describe the dynamic characteristics needed to provide valid loads and accelerations. Airplane dynamic responses should be calculated with a complete integrated airframe and engine analytical model. The airplane model should be comparable to those used for certification flutter and dynamic gust analyses. The engine and nacelle model would normally be to the same level of detail as the model used for FAR 33.94 test simulation. Optionally a simplified engine model may be used in the windmilling analysis if shown to be valid for the airplane/engine configuration and the frequencies of interest.

cc:

Mr. Joseph Hawkins
Department of Transportation
Federal Aviation Administration - ARM-1
800 Independence Avenue S.W.
Washington, D.C. 20591

Mr. Stewart Miller
Department of Transportation
Federal Aviation Administration - ANM-110
1601 Lind Avenue S.W.
Renton, WA 98055

Mr. Vic Card
UK Civil Aviation Authority
Aviation House
Gatwick Airport RH6 OYR
England

Mr. Thaddée Sulocki
Joint Aviation Authorities
Saturnusstraat 10
2130 KA Hoofddorp
The Netherlands

Mr. Craig Bolt
Pratt & Whitney
400 Main Street
Mail Stop 162-24
East Hartford, CT 06108

Ms. Jacquelin Smith
Department of Transportation
Federal Aviation Administration - ARM-209
800 Independence Avenue S.W.
Washington, D.C. 20591

FAA Action – Not Available